THz near-filed microscopy technique and applications with sub-wavelength aperture probes

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1. Introduction: some near-field optics concepts

2. Historical perspective: THz imaging technology

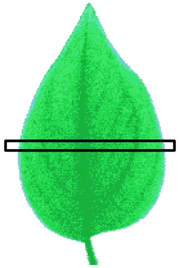
3. THz imaging applications:

E-field mapping in space and time

4. THz surface waves and metallic resonators

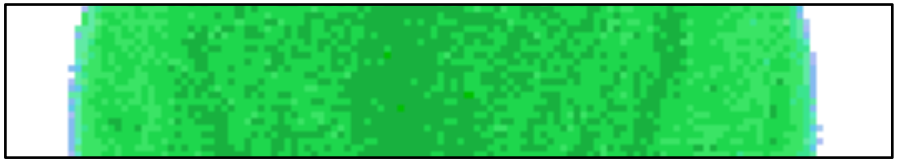
5. Aperture-type THz near-field probes

THz imaging: *Diffraction Limit*



Hu and Nuss
(1995)

λ=300μm

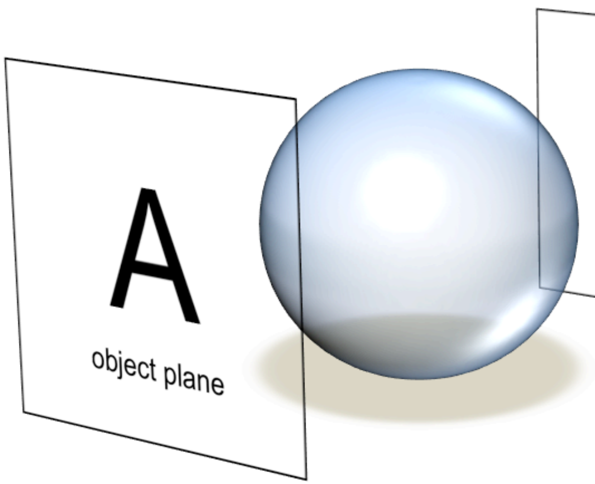


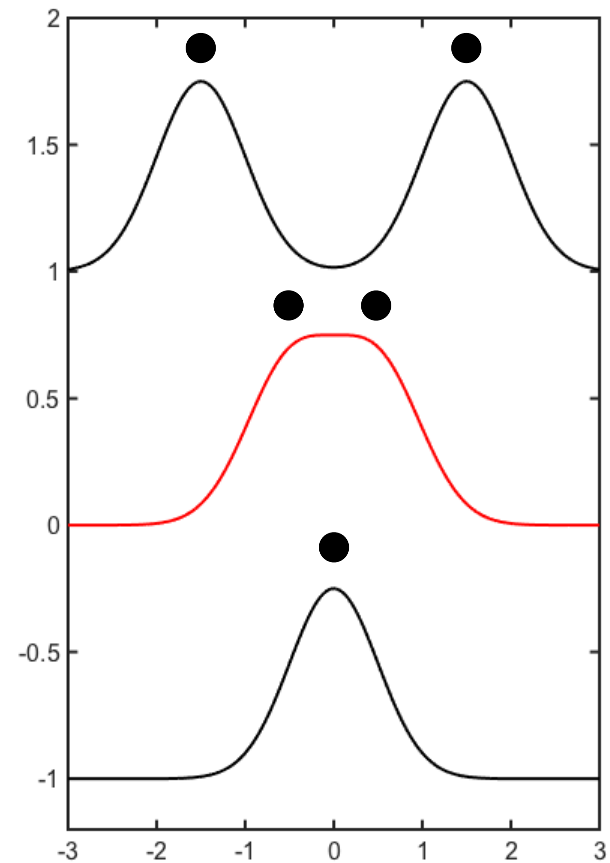
Spatial Resolution Limit

$$d = \frac{\lambda}{2n \sin\alpha}$$

Ernst Abbe (c. 1873)

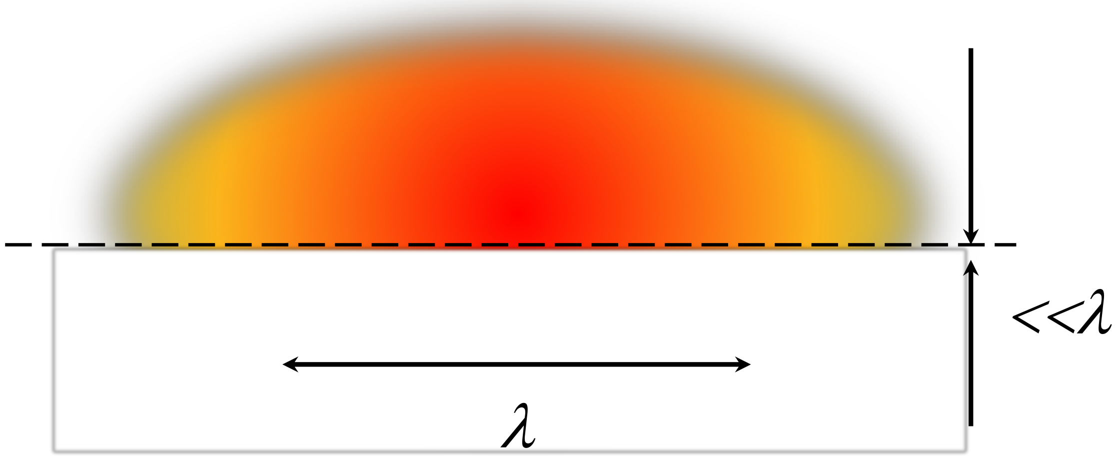
Point-spread function of imaging system

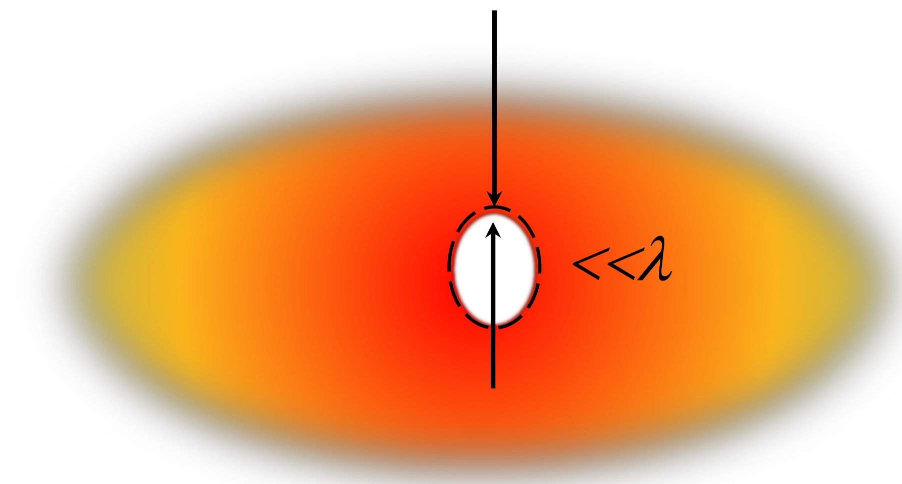




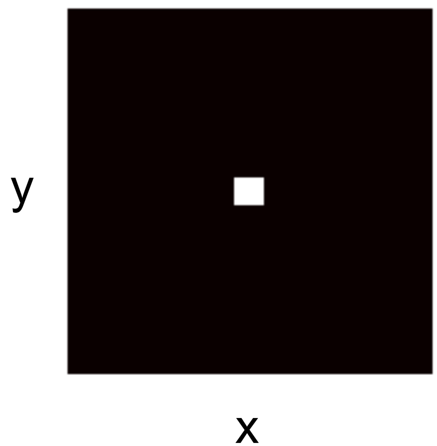
Resolving two points

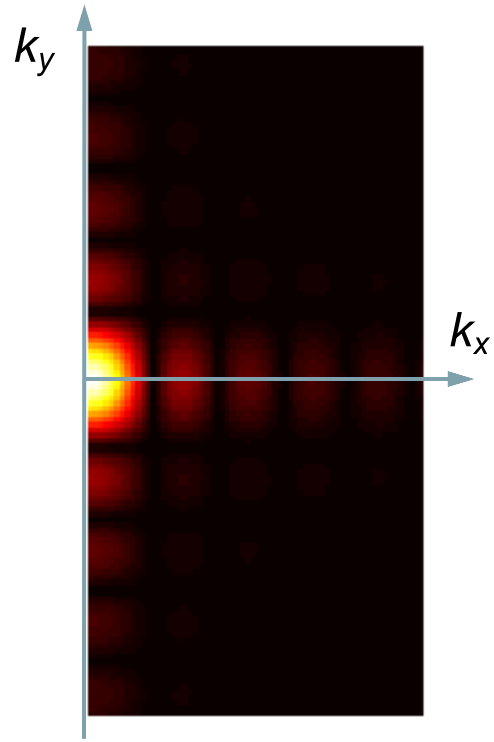
EM field distribution at Interfaces





Angular spectrum representation of the EM fields





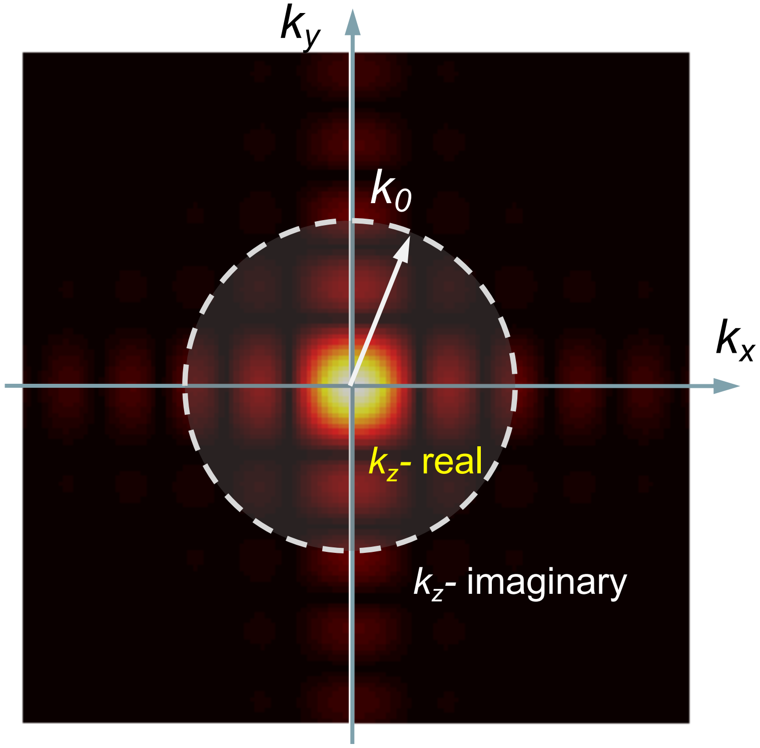
Spatial distribution ⟷ Spatial frequency distribution

Fourier Transform

$$E = E_0 \, exp(ik_0 r - i\omega t)$$

$$k_0^2 = k_x^2 + k_y^2 + k_z^2$$

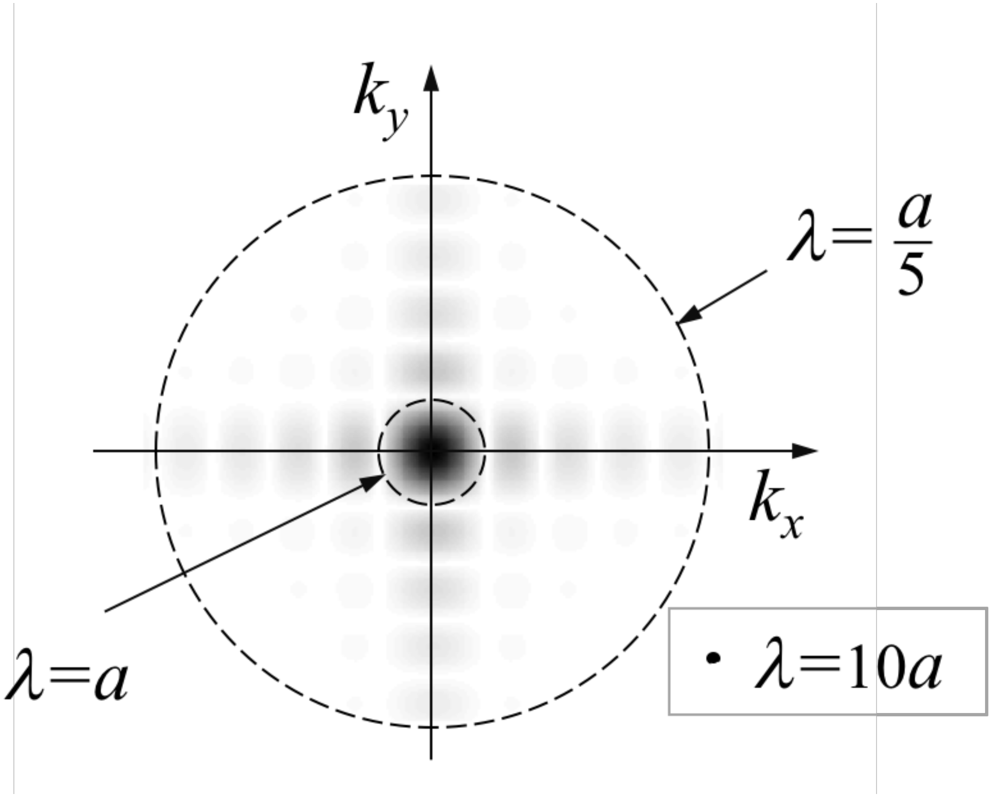
Evanescent waves



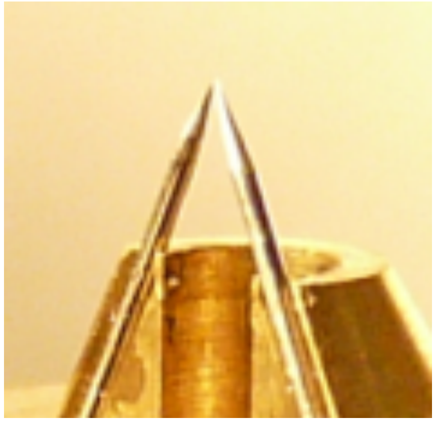
Imaginary k_z components – evanescent waves

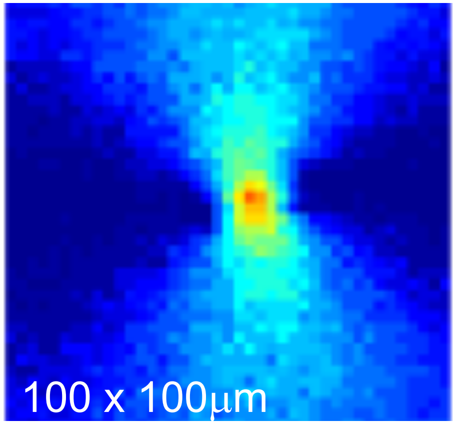
- localized near surface

Evanescent waves for confined field of size a

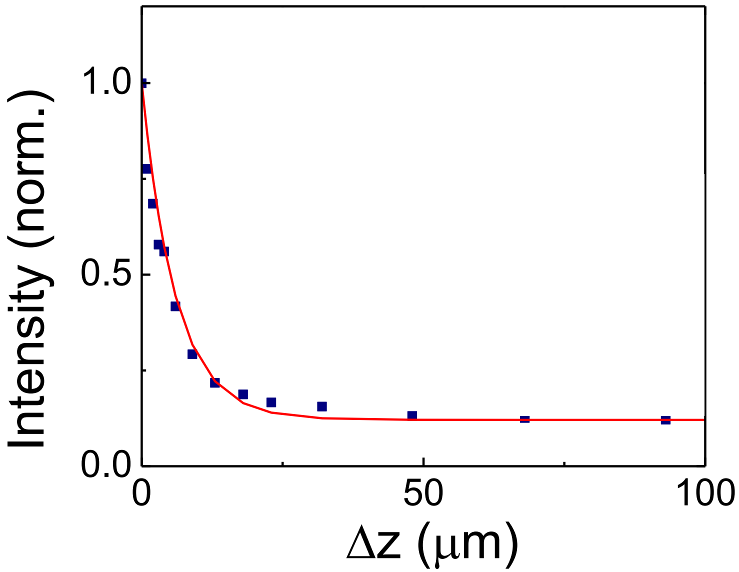


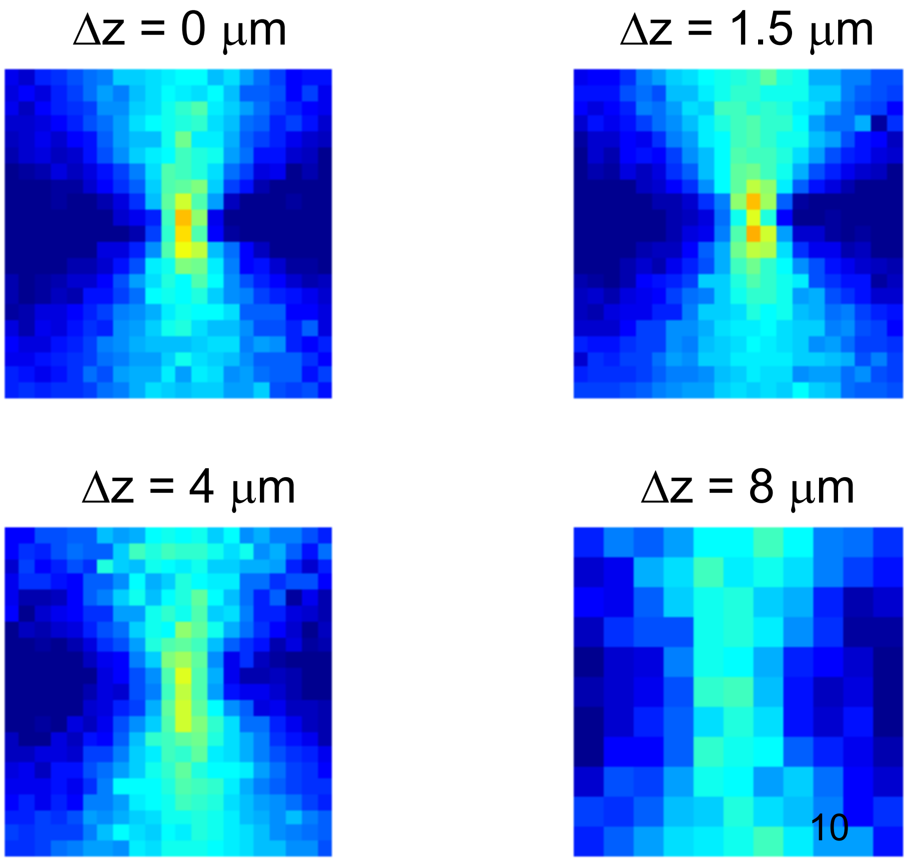
Sub-wavelength field confinement





λ ~200 μm



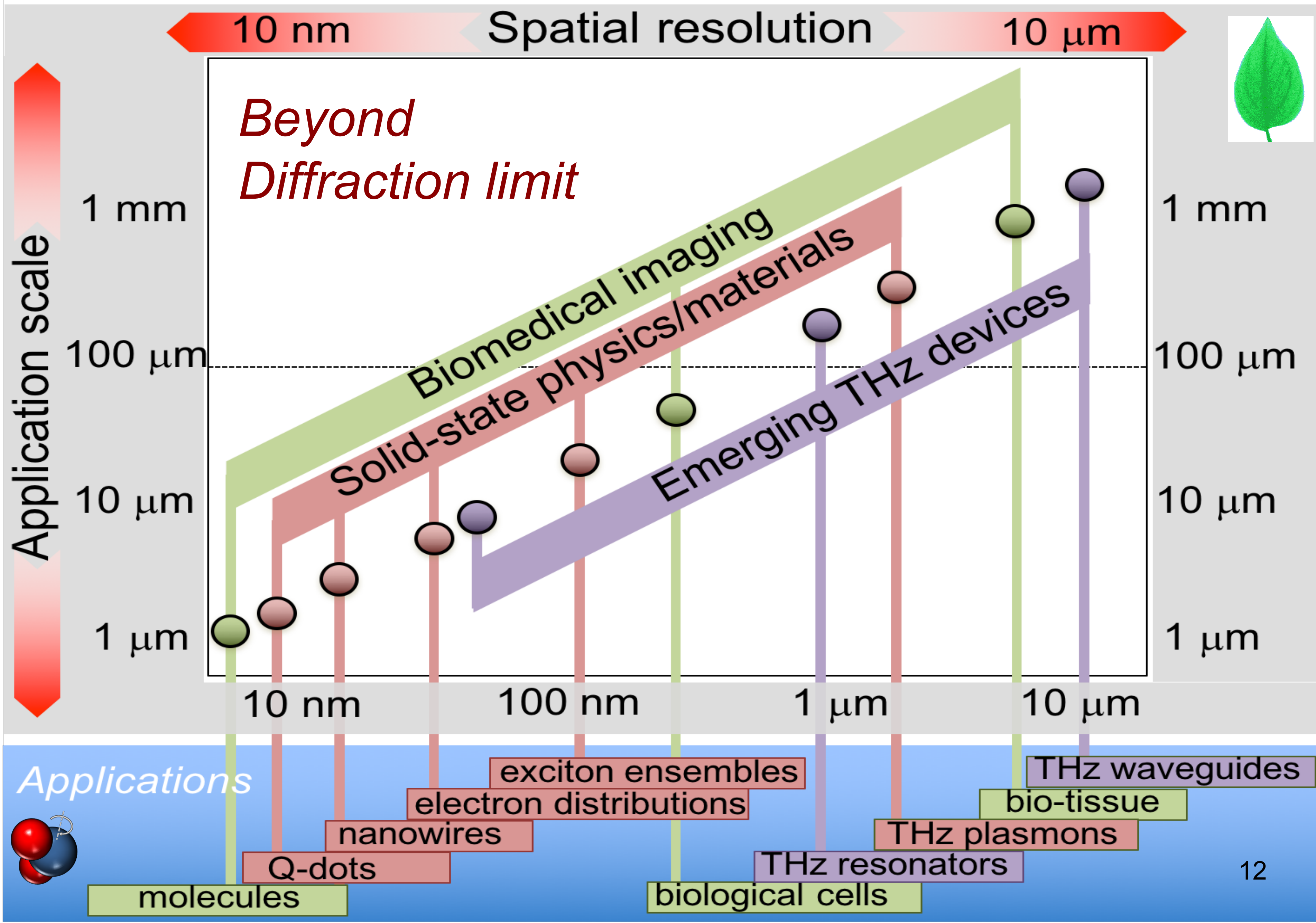


Opt. Express **20**, 6197 (2012)

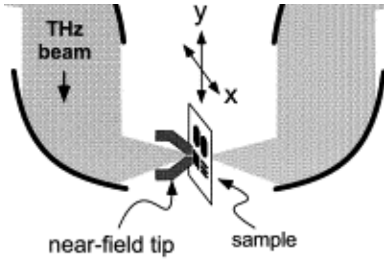
Breaking the diffraction limit in the THz range

$$\frac{\lambda}{r} = 1 - 100{,}000$$

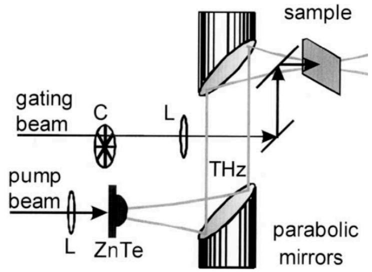
THz Near-field Imaging Technology and Applications



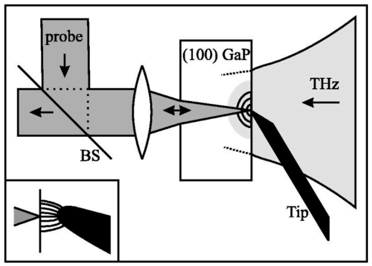
Progress in development of THz microscopy



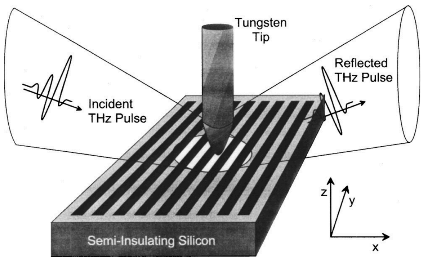
Hunsche et al., 1998



Chen et al., 2000

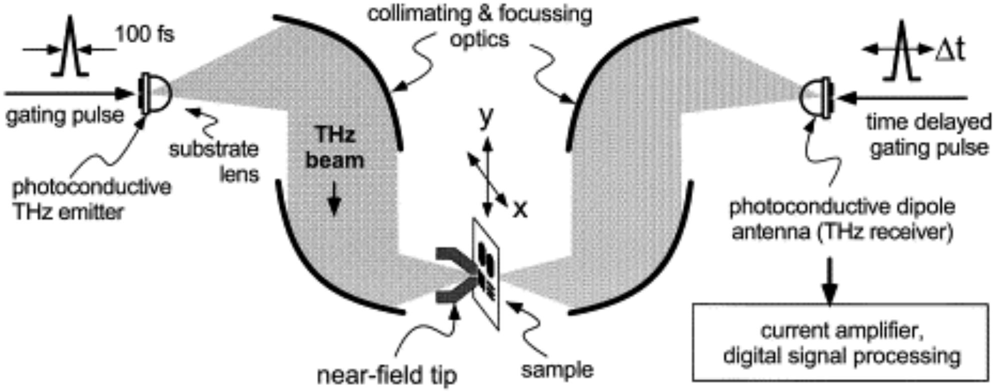


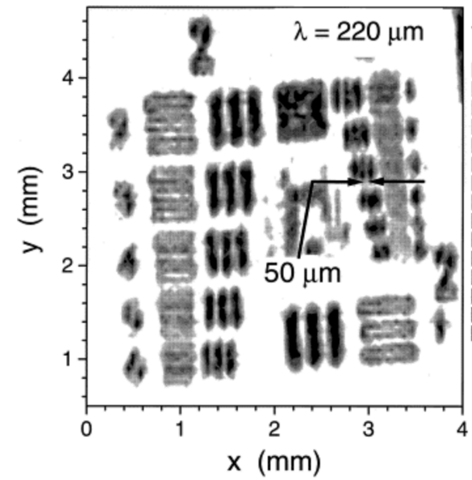
Van der Valk et al., 2002



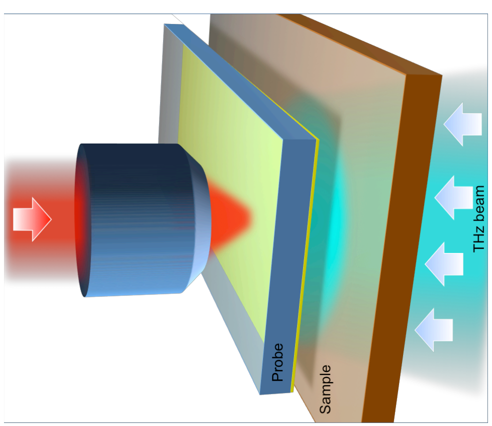
Chen et al., 2003

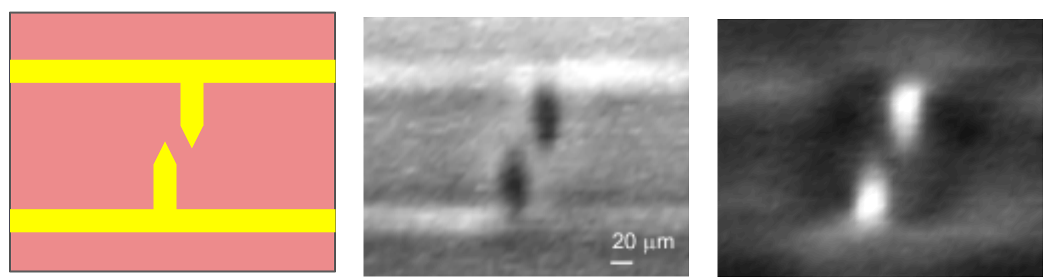
Early development of THz microscopes





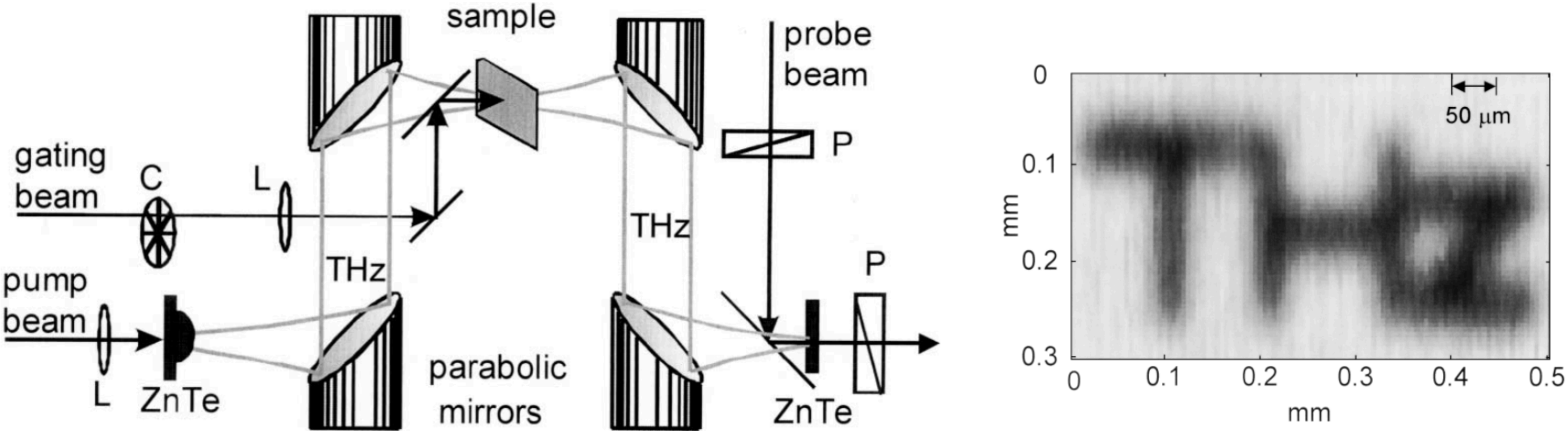
Hunsche et al. *OPTICS COMM* (1998)





Mitrofanov et al. *J. STQE* **103**, 600 (2001)

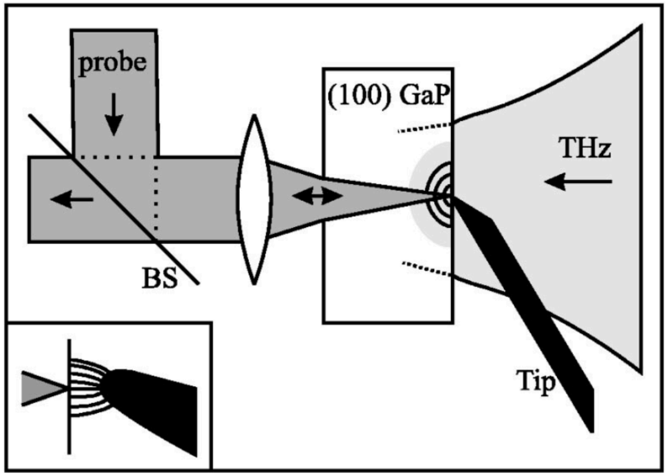
Near-field THz source modulation - ‘Dynamic Aperture’ (THz-TDS)



Chen et al. *OPTICS LETTERS* 25 (2000)

Early development of THz microscopes

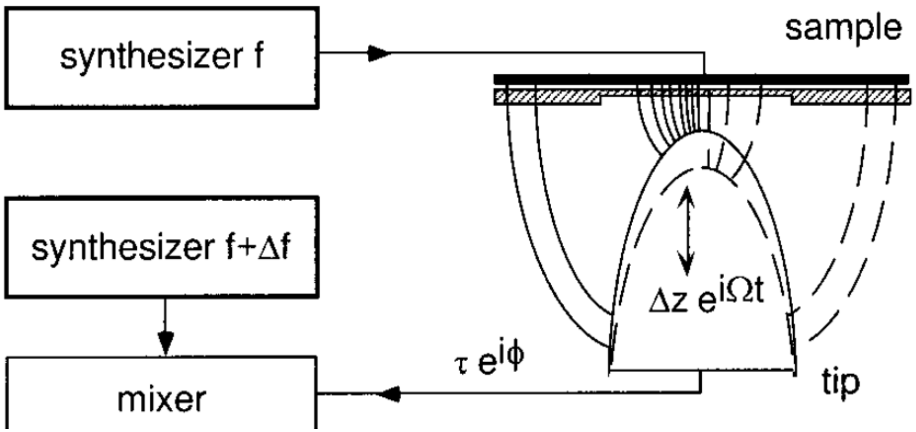
Electro-optic near-field probes (THz-TDS)

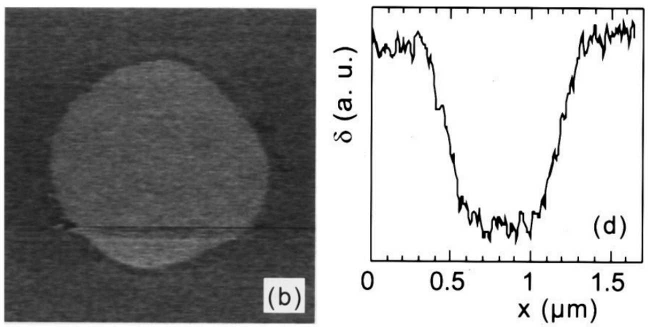


Van der Valk et al., APPL. PHYS. LETT. (2002)

Early development of THz microscopes

STM Tip - Microwave transmission (1 GHz)

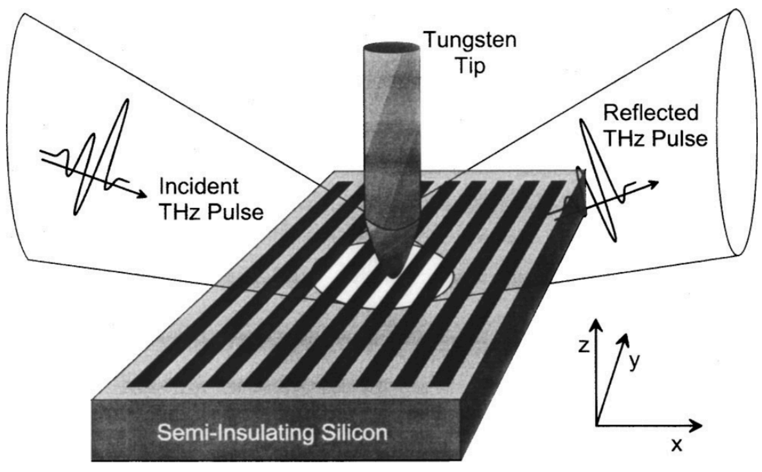


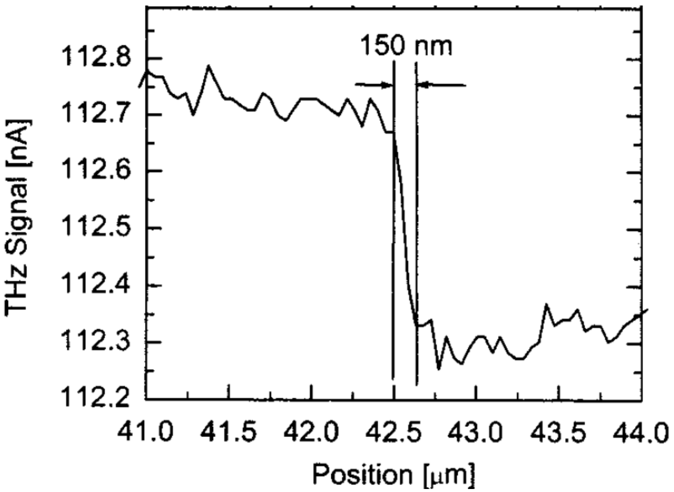


B. Knoll, F. Keilmann et al., APPL. PHYS. LETT. 70, 2667 (1997)

Early development of THz microscopes

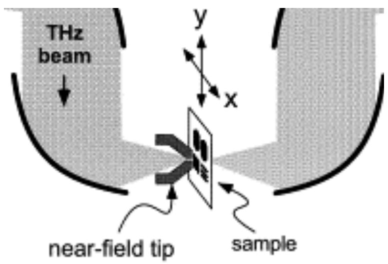
Scattering Tip near-field microscopy (THz-TDS)



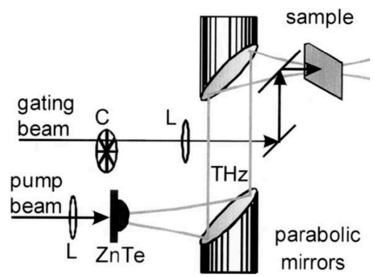


Chen et al., APPL. PHYS. LETT. 83, 3009 (2003)

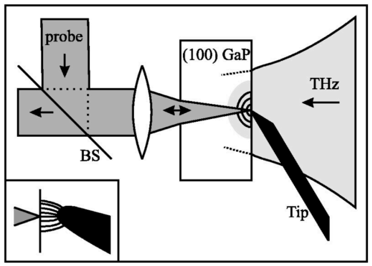
Progress in development of THz microscopy



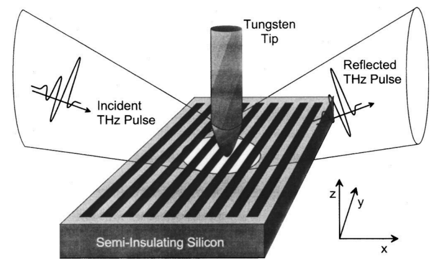
Hunsche et al., 1998



Chen et al., 2000



Van der Valk et al., 2002



Chen et al., 2003

Near-field probes with integrated THz detectors

Sub-wavelength THz generation

Use of patterns instead of apertures

Signal processing: adaptive imaging and compressive sensing

EO materials/ultrathin crystals

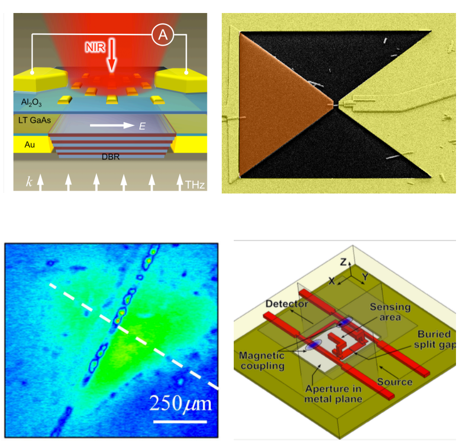
High-*E* THz sources

Spectral filtering

Higher order modulation techniques

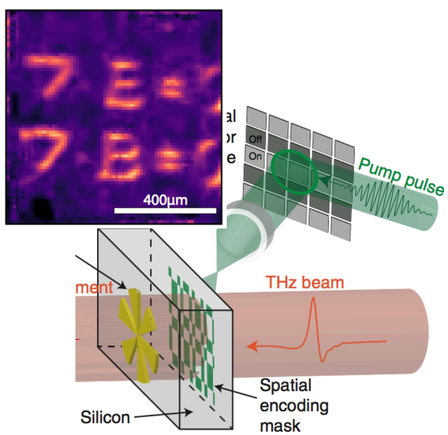
Surface plasmons

Detection of a THz driven tunneling current

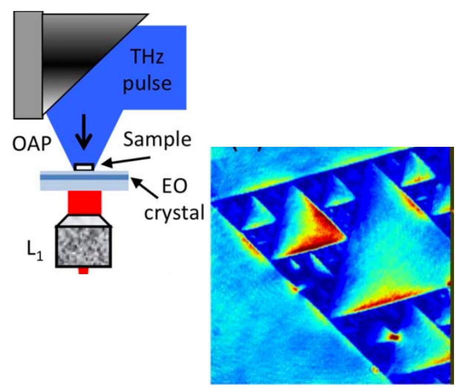


Serita (2012)

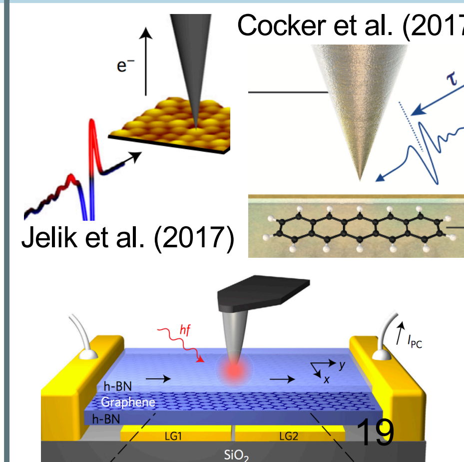
Grzyb (2016)



Rayko et al., 2016



Blanchard & Tanaka, 2016



Cocker et al. (2017)

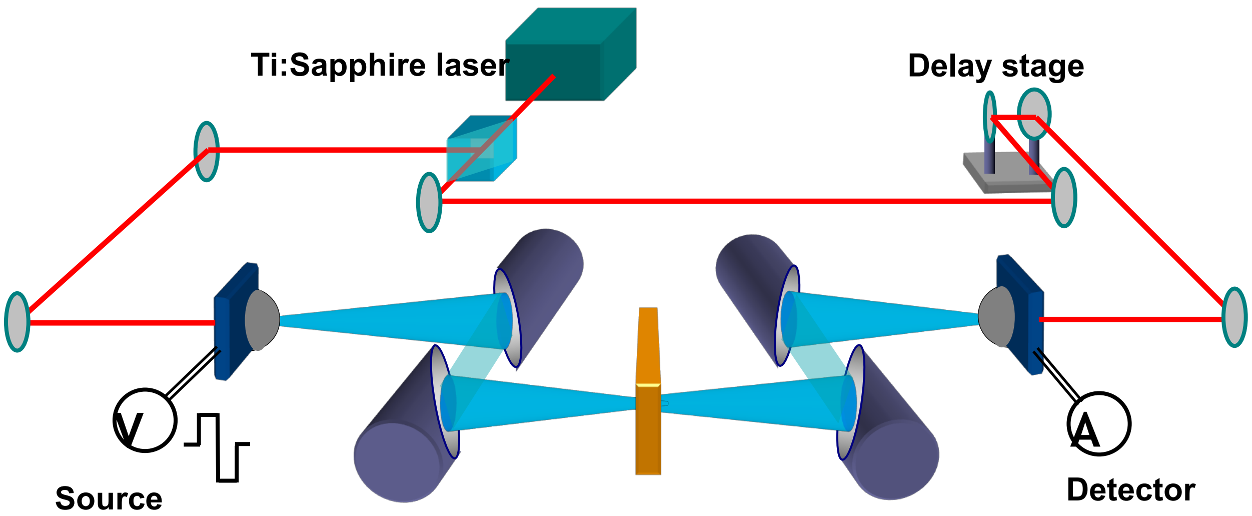
Jelik et al. (2017)

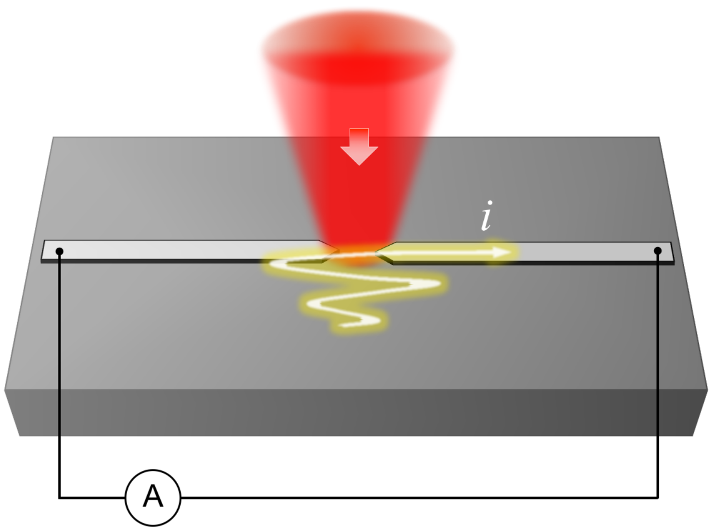
Alonso-Gonzalez et al. (2017)

THz imaging applications:

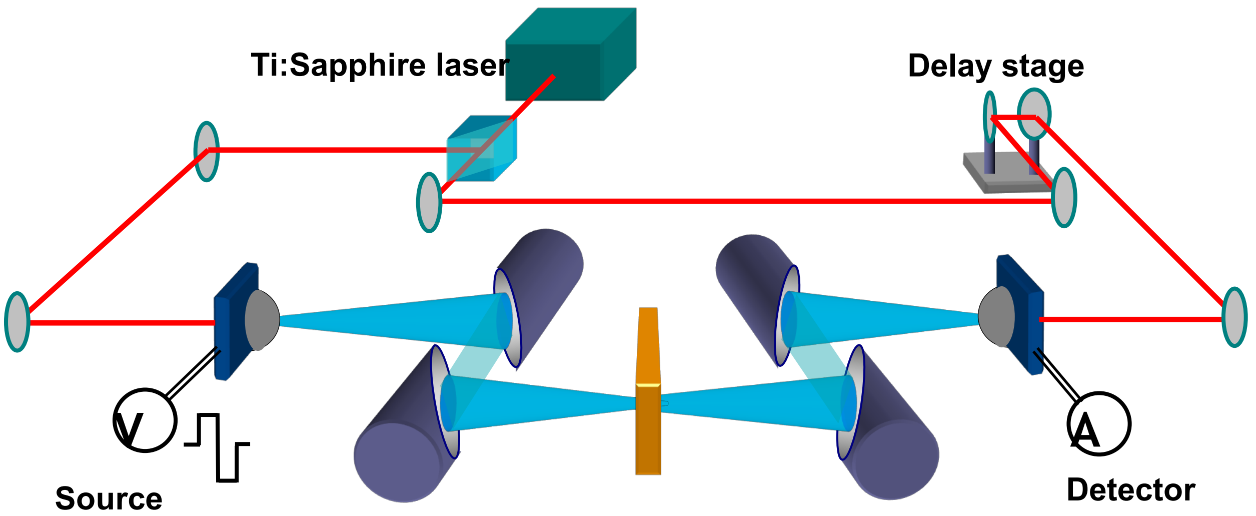
E-field mapping in space and time

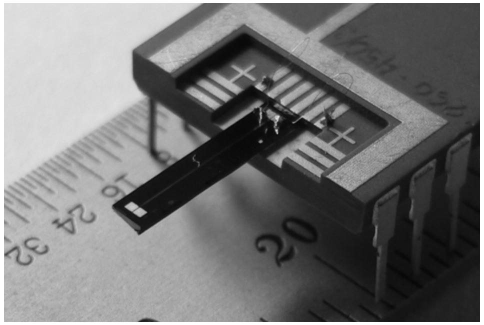
THz-time-domain spectroscopy system

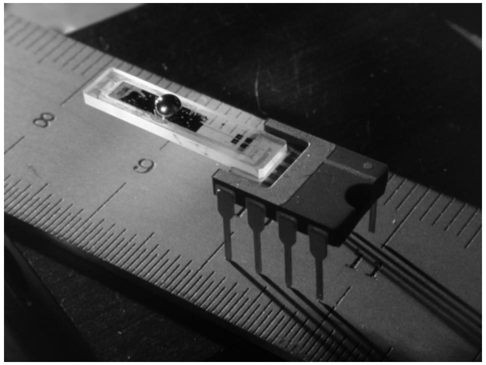


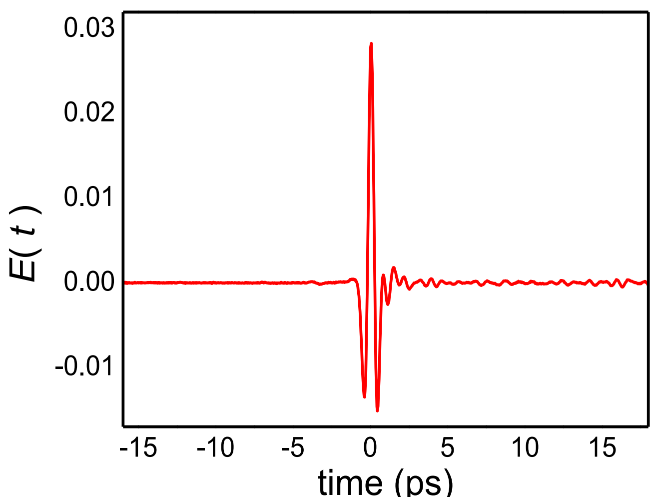


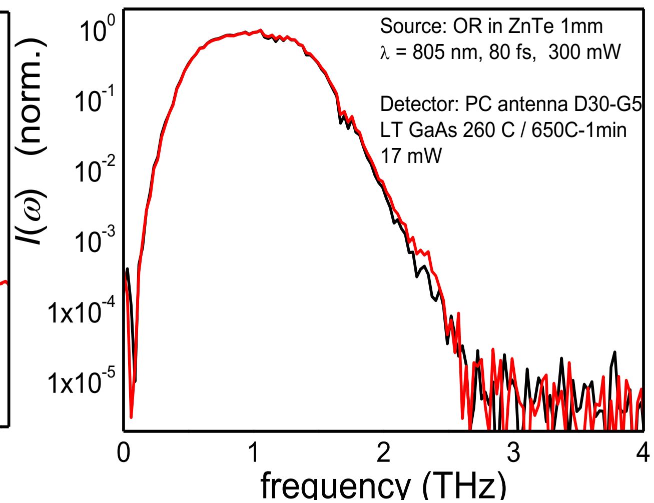
THz-time-domain spectroscopy system



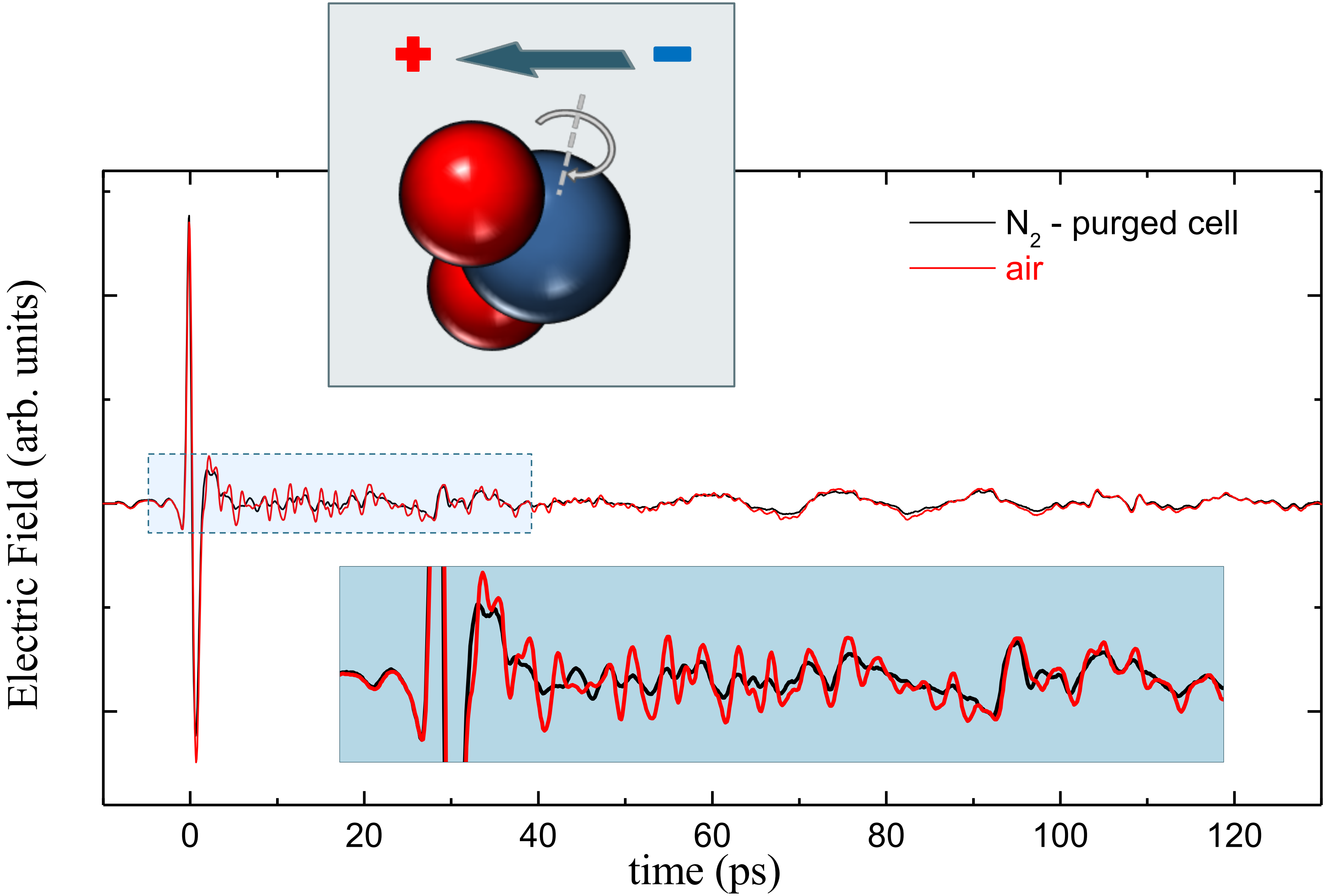




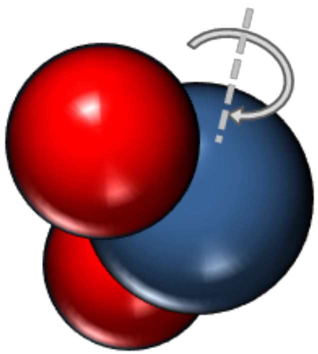


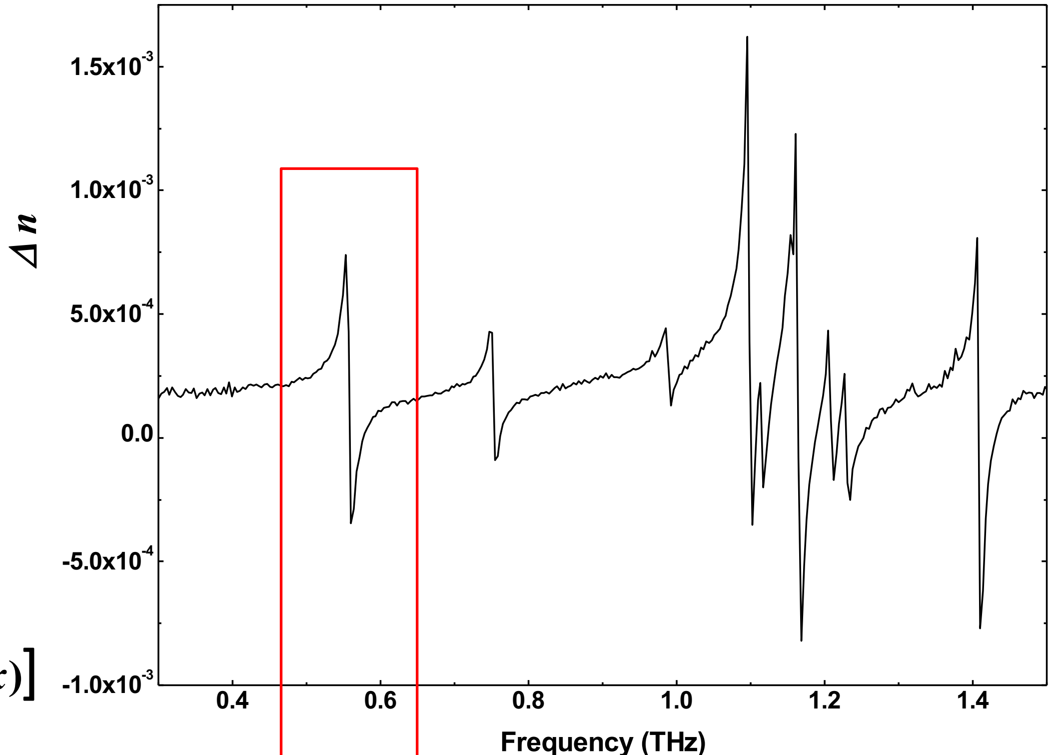


Application of THz-TDS: THz resonator – H_2O molecule



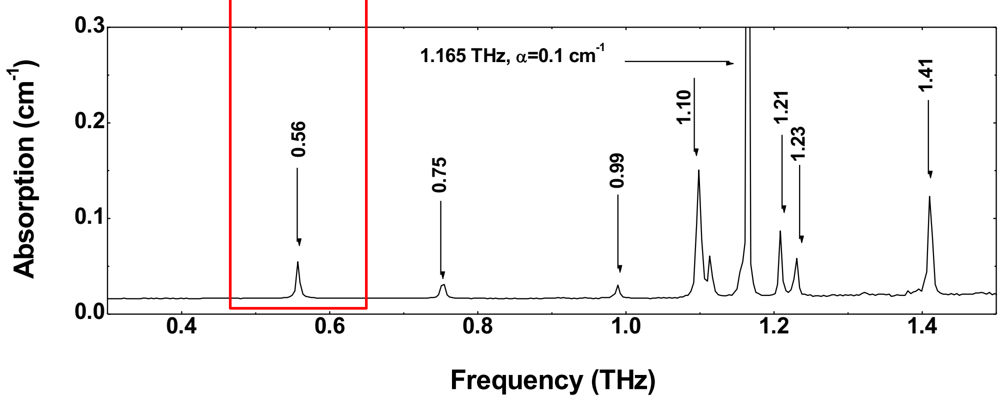
Application of THz-TDS: THz resonator – H_2O molecule





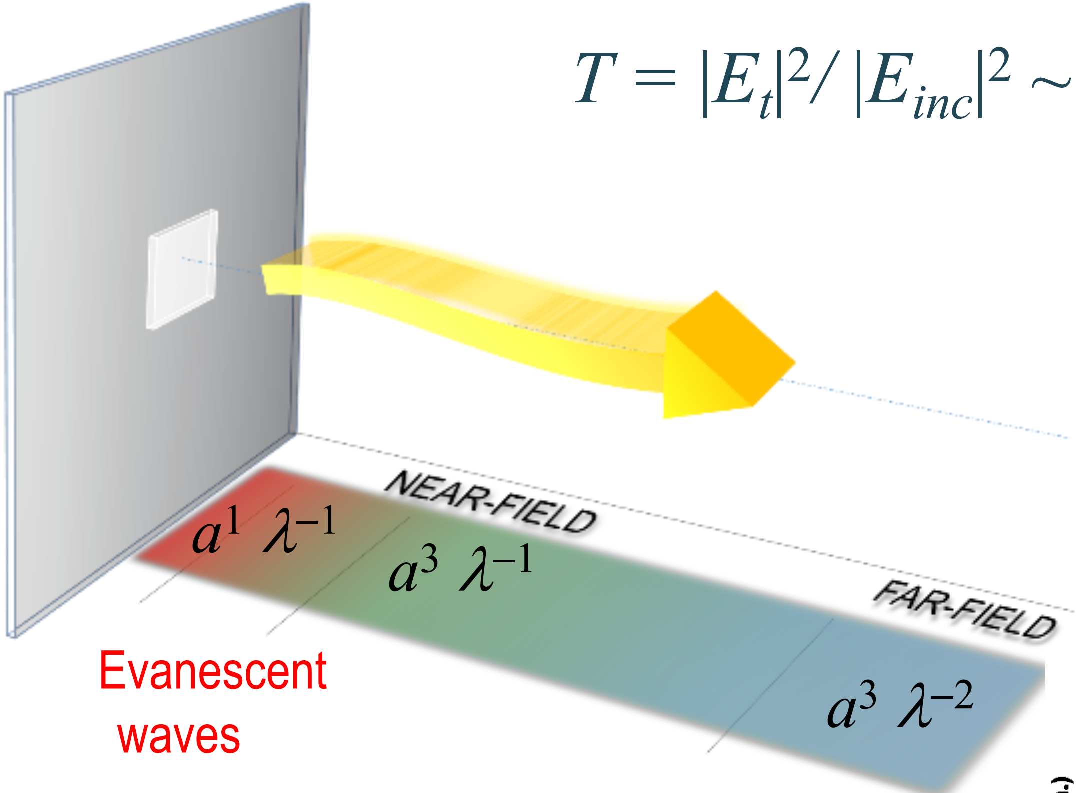
$$\mathrm{Re}\left[\hat{n}(\omega)\right] = \frac{c}{\omega l}\left[\varphi(\omega, x+l) - \varphi(\omega, x)\right]$$

$$\mathrm{Im}\left[\hat{n}(\omega)\right] = \frac{c}{\omega l}\left[\ln\left(\frac{E(\omega, x+l)}{E(\omega, x)}\right)\right]$$



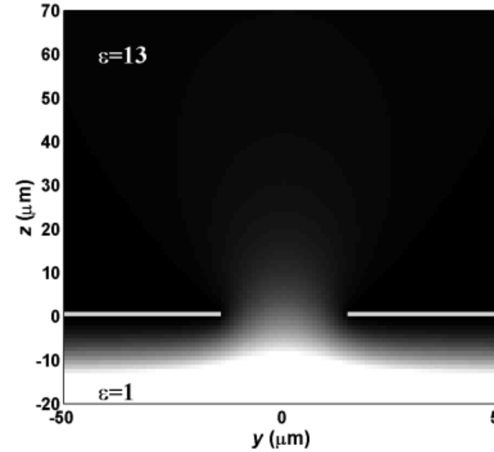
Wave transmission through subwavelength apertures

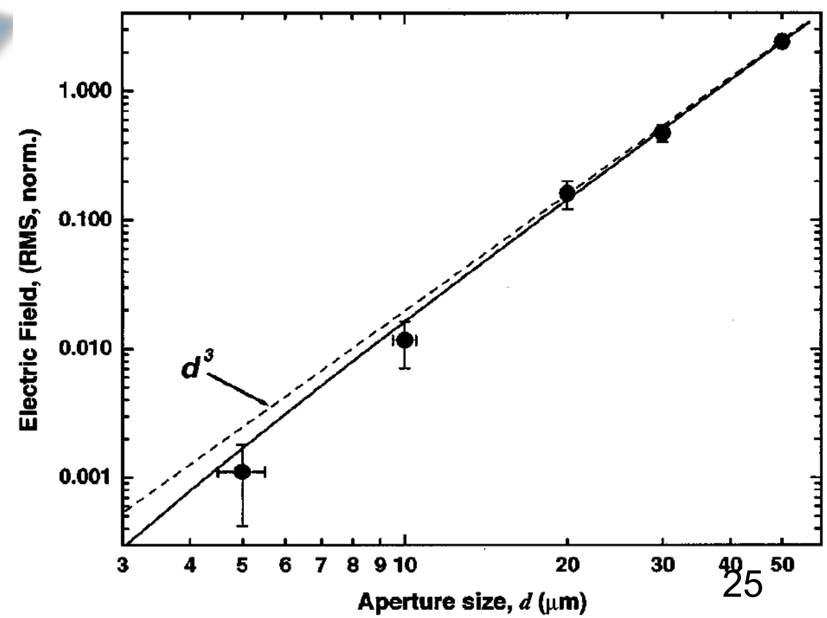
$$T = |E_t|^2 / |E_{inc}|^2 \sim a^6$$



Evanescent waves

Propagating waves

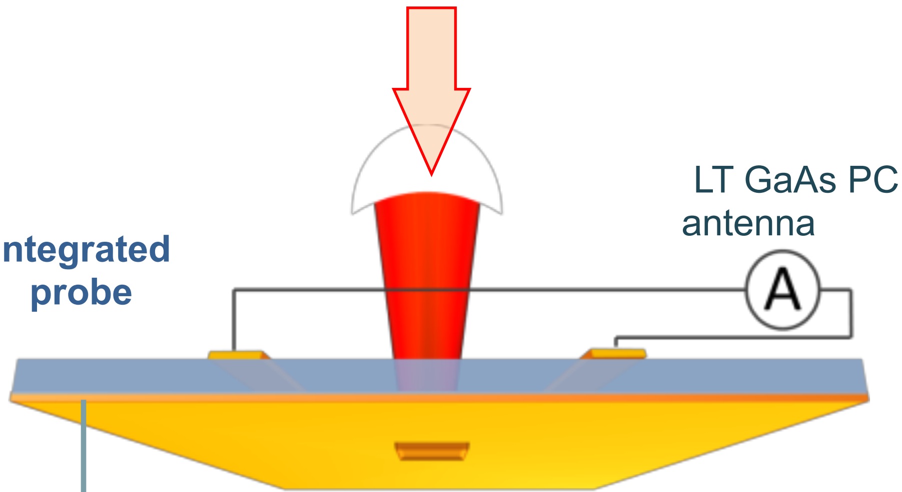


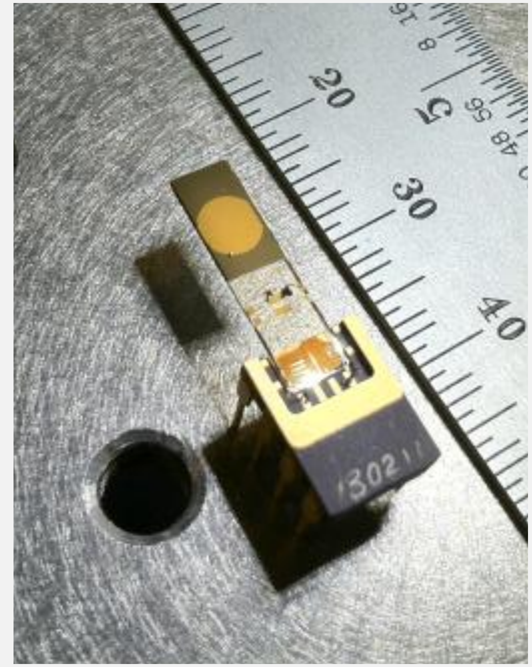


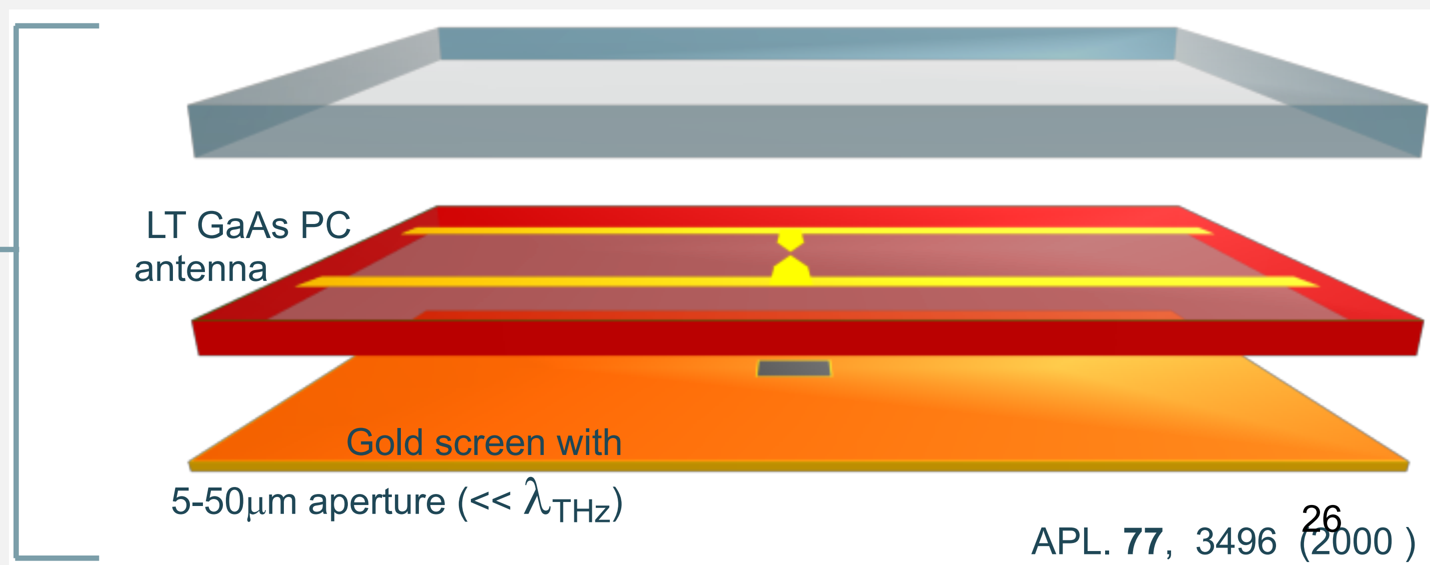
Mitrofanov et al., APL **77**, 3496 (2000)
APL 79, 907 (2001)

Adam, J IRMTW **32**, 976 (2011)

Integrated sub-wavelength aperture probe

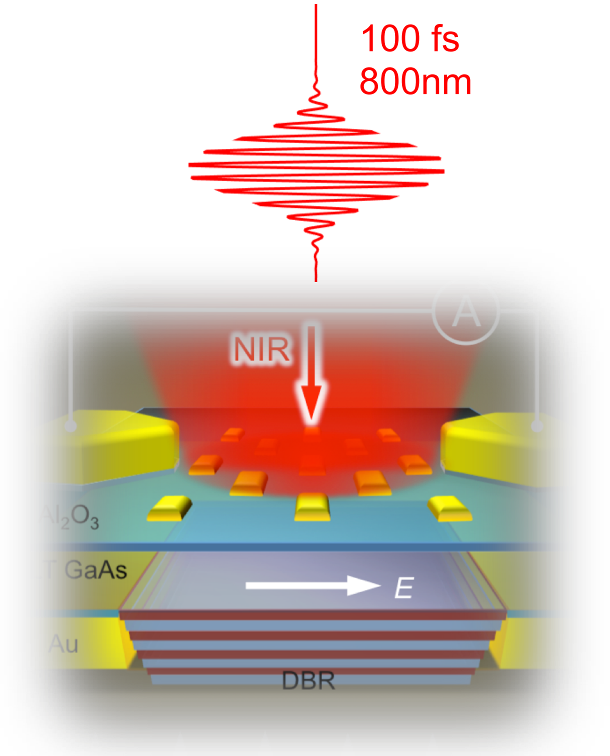


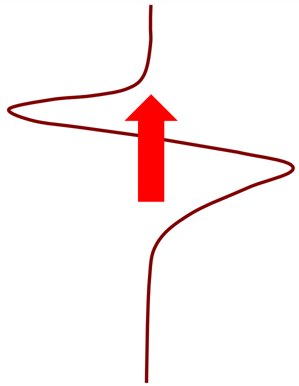


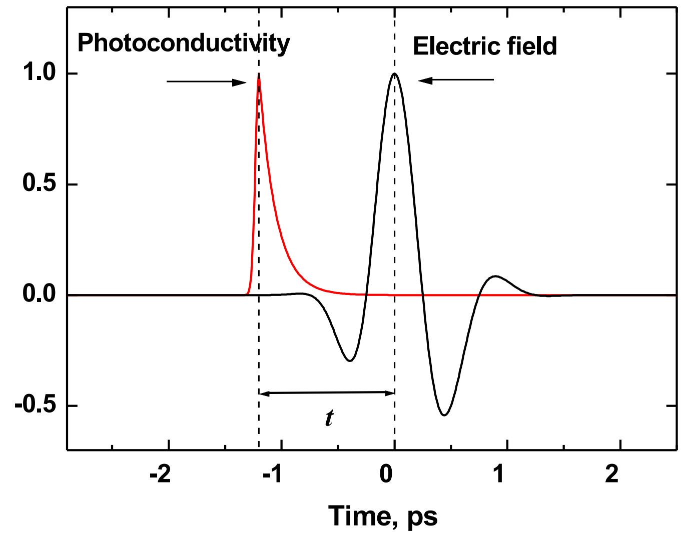


APL. **77**, 3496 (2000)

Photoconductive Probing







$$I_A(t) = \int \sigma(t'-t)E_{THz}(t')dt'$$

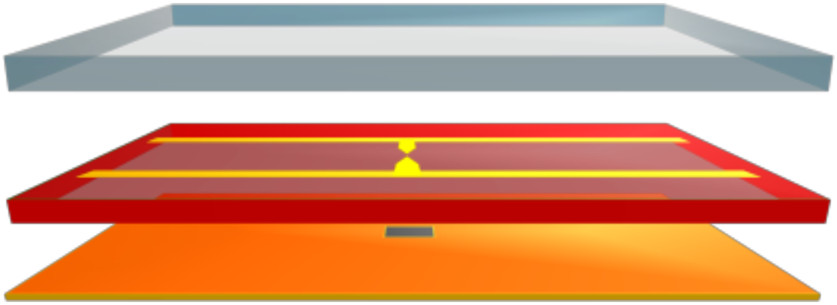
$$E(t), E(\omega), \phi(\omega)$$

material: LT GaAs

gating pulse: λ_c = 800 nm, τ = 100 fs

Bandwidth: 3 THz

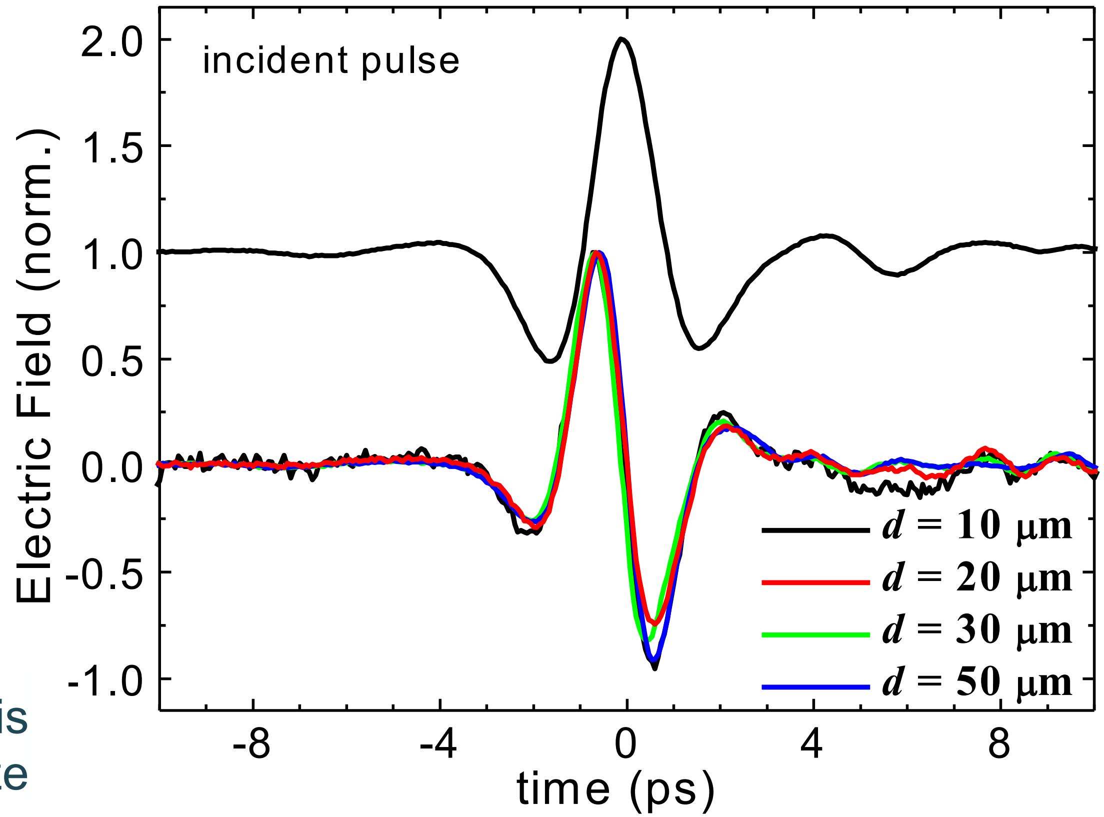
Frequency response of the aperture probe



Aperture much smaller than the wavelength

$$E(\omega) \sim \omega$$

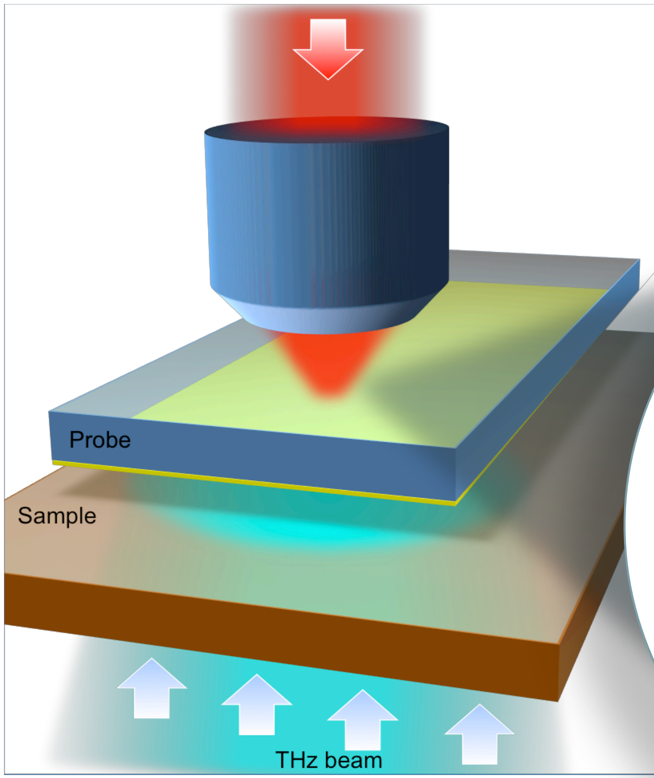
$$\phi(\omega) = \pi/2$$

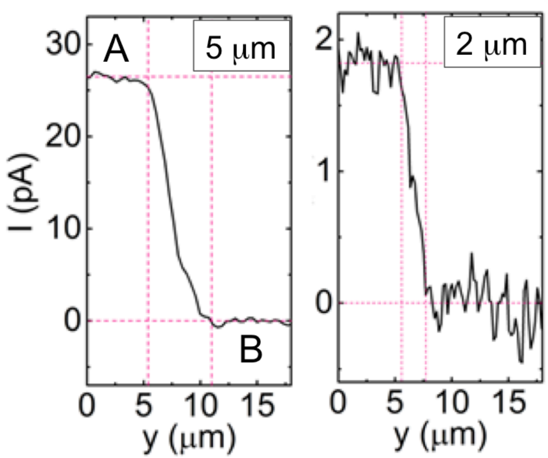


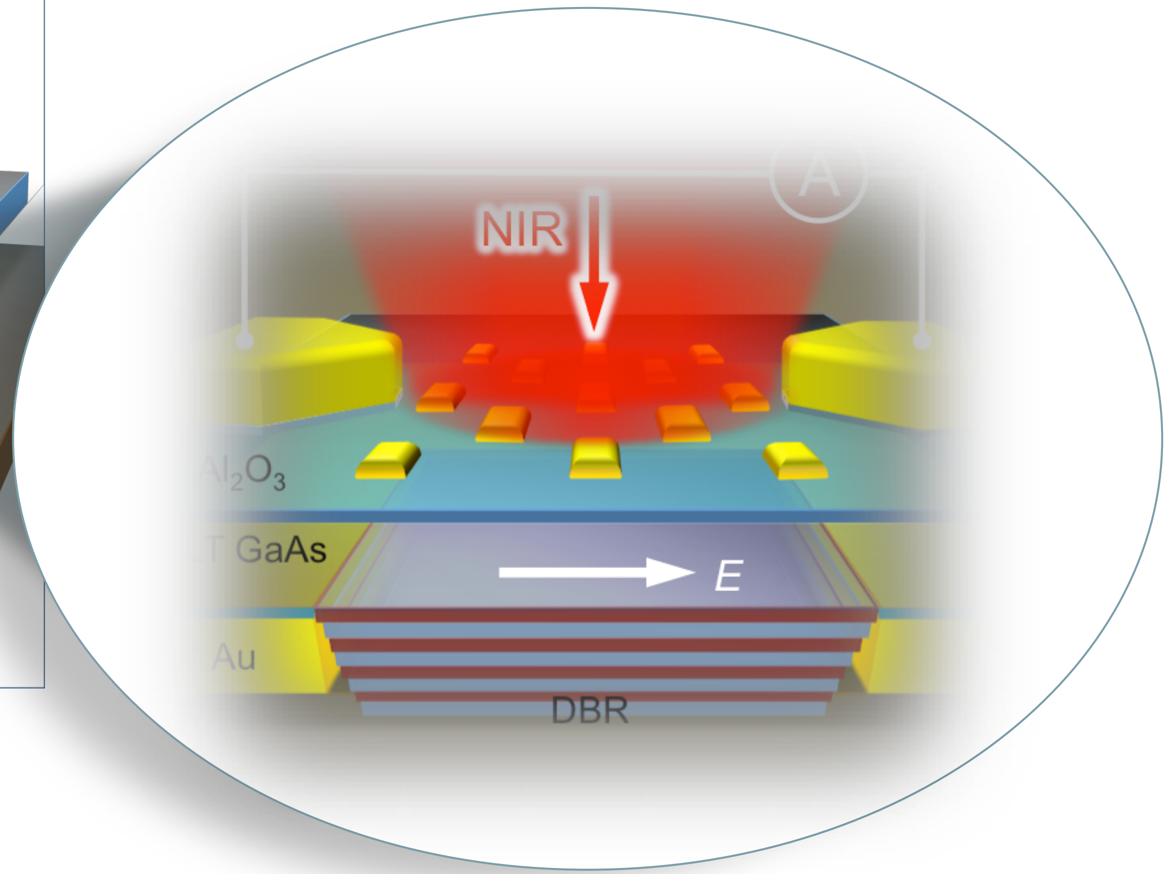
Waveform deformation is independent of the aperture size

APL. **77**, 3496 (2000)

High-resolution near-field probes

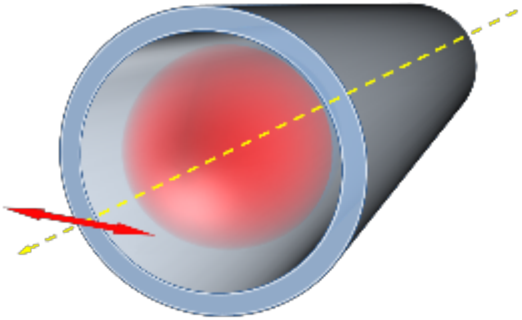


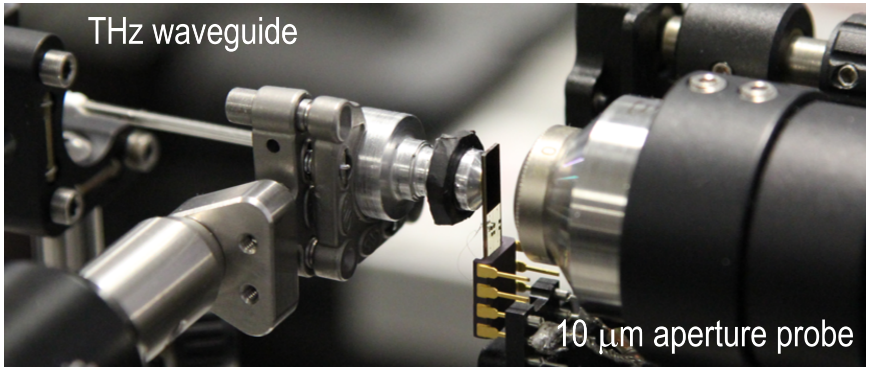


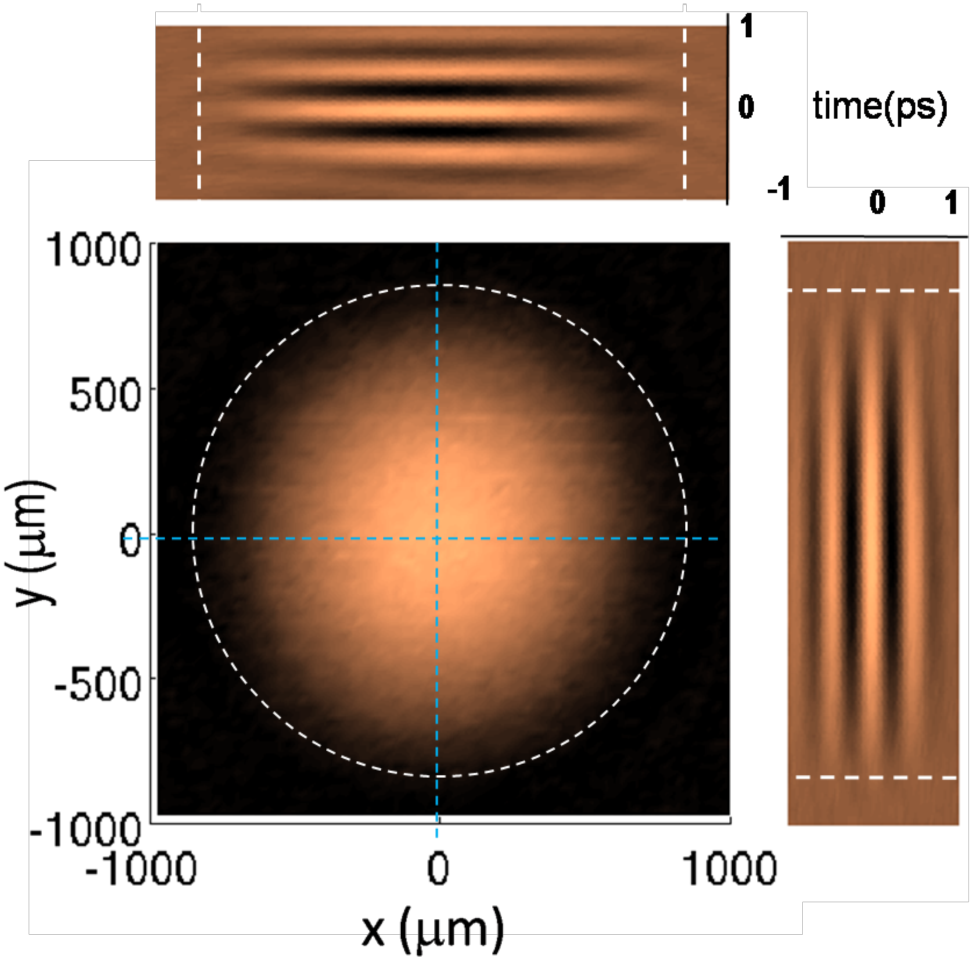


ACS Photonics (2015)

Applications in THz technology research: *Waveguides*



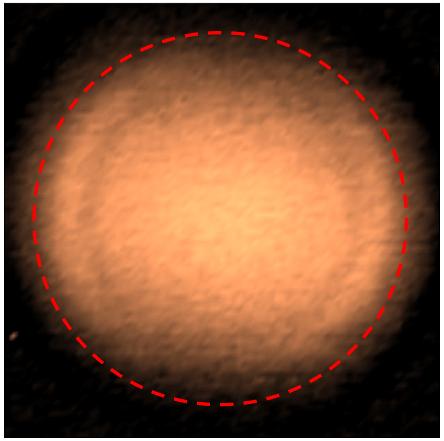




APL. **94**, 171104 (2009)

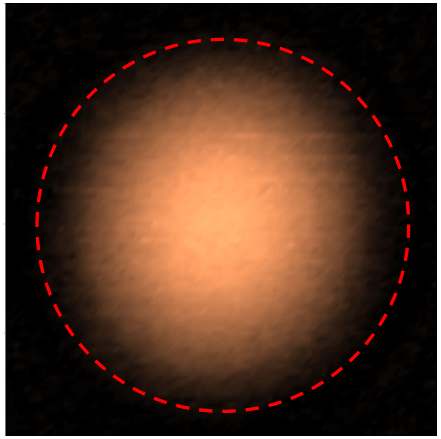
Mode profiles: low loss waveguides

Dominant mode profiles



TE_{11}

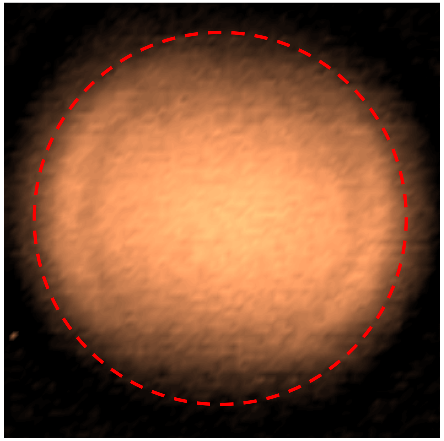
hollow metallic waveguide



HE_{11}

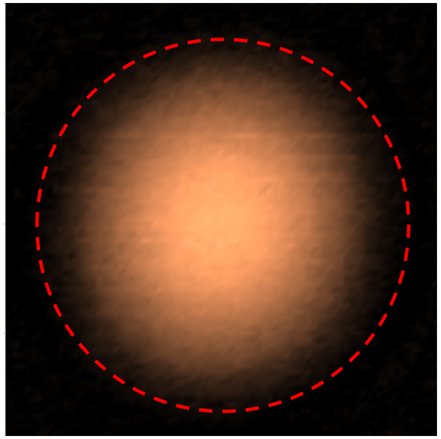
similar waveguide with a PS inner coating

Dominant mode profiles



TE_{11}

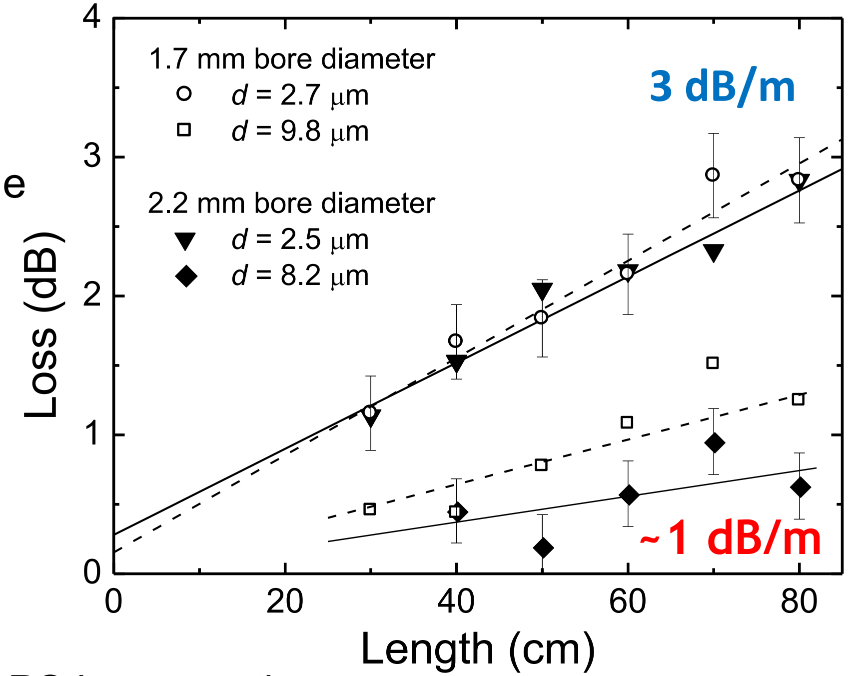
hollow metallic waveguide



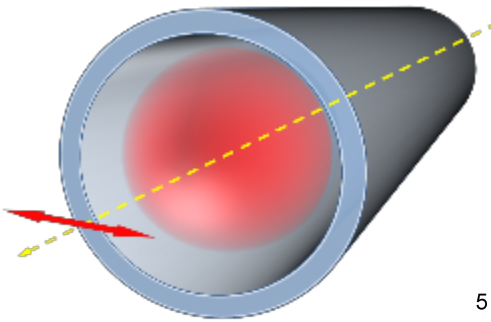
HE_{11}

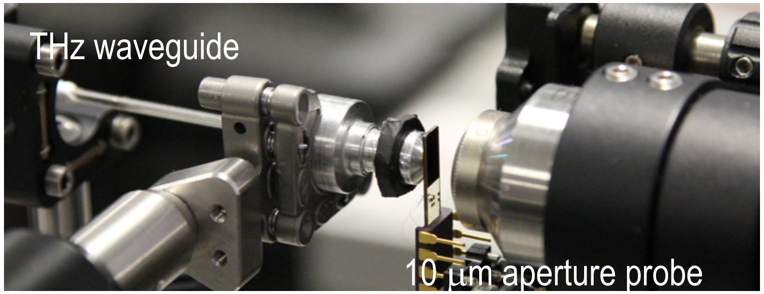
similar waveguide with a PS inner coating

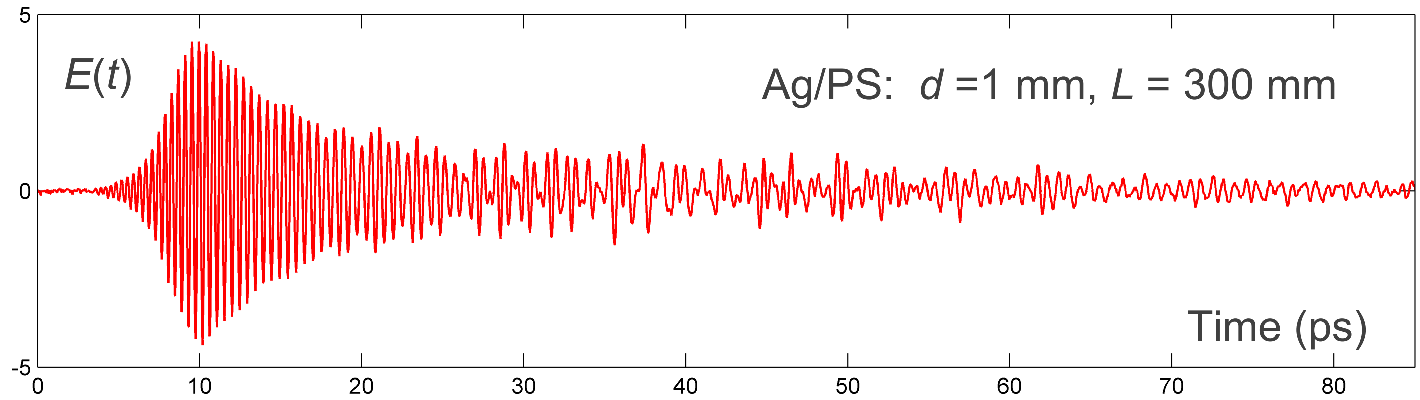
Transmission Loss at 2.5THz

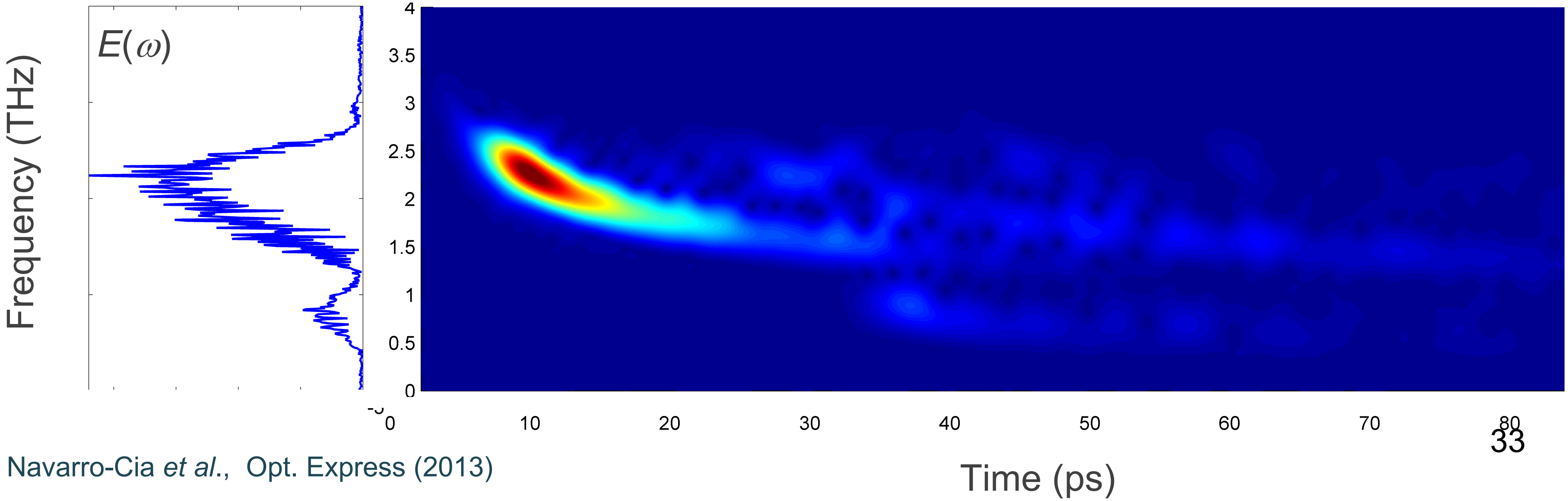


Applications in THz technology research: *Waveguides*



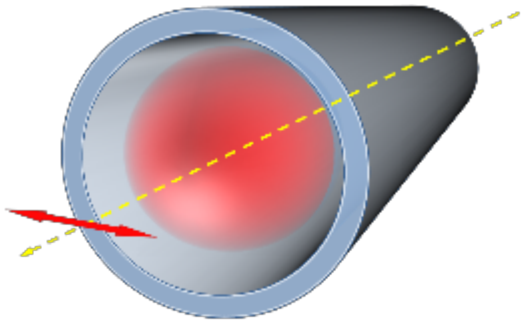


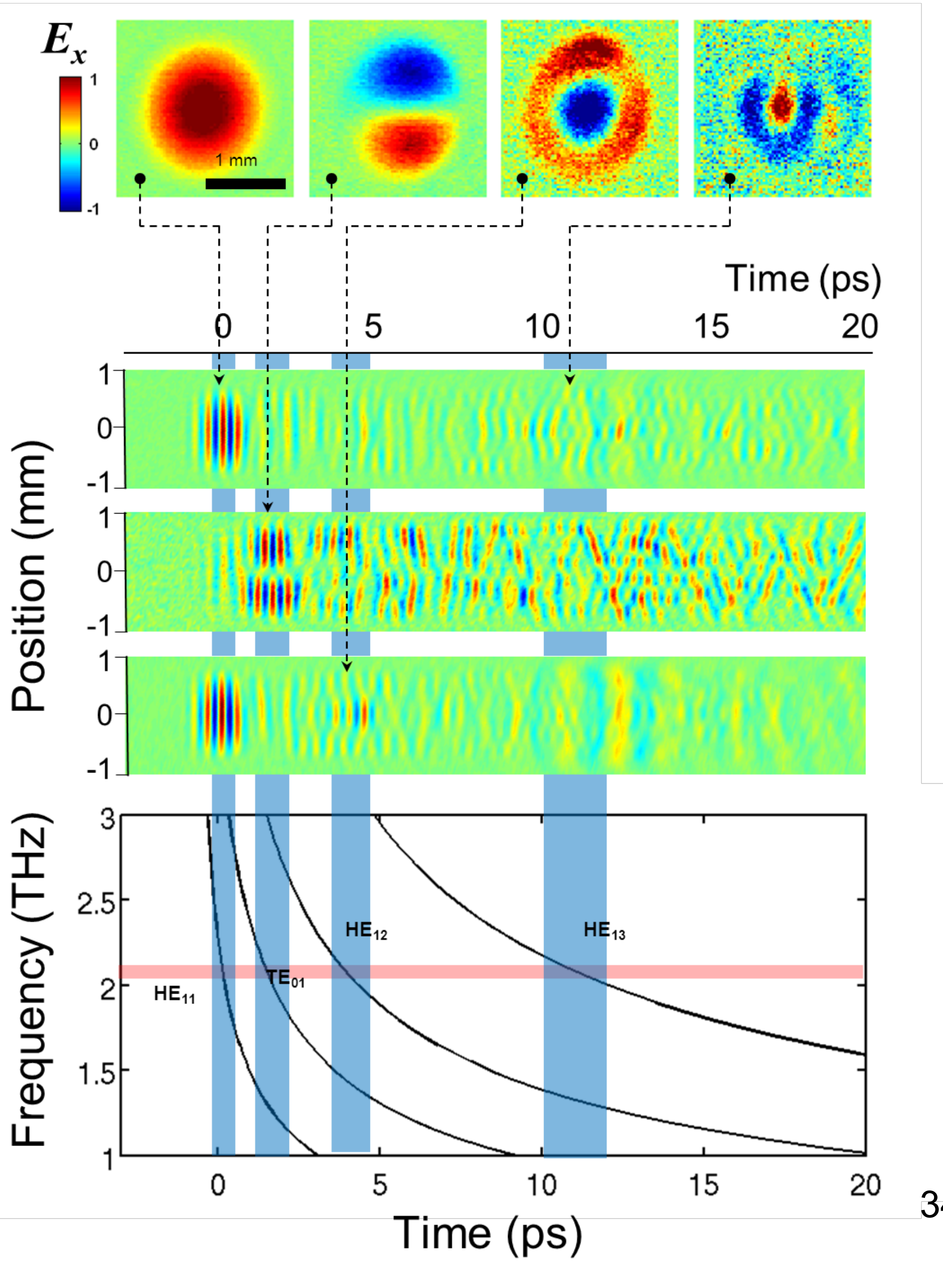




Navarro-Cia *et al.*, Opt. Express (2013)

Applications in THz technology research: *Waveguides*

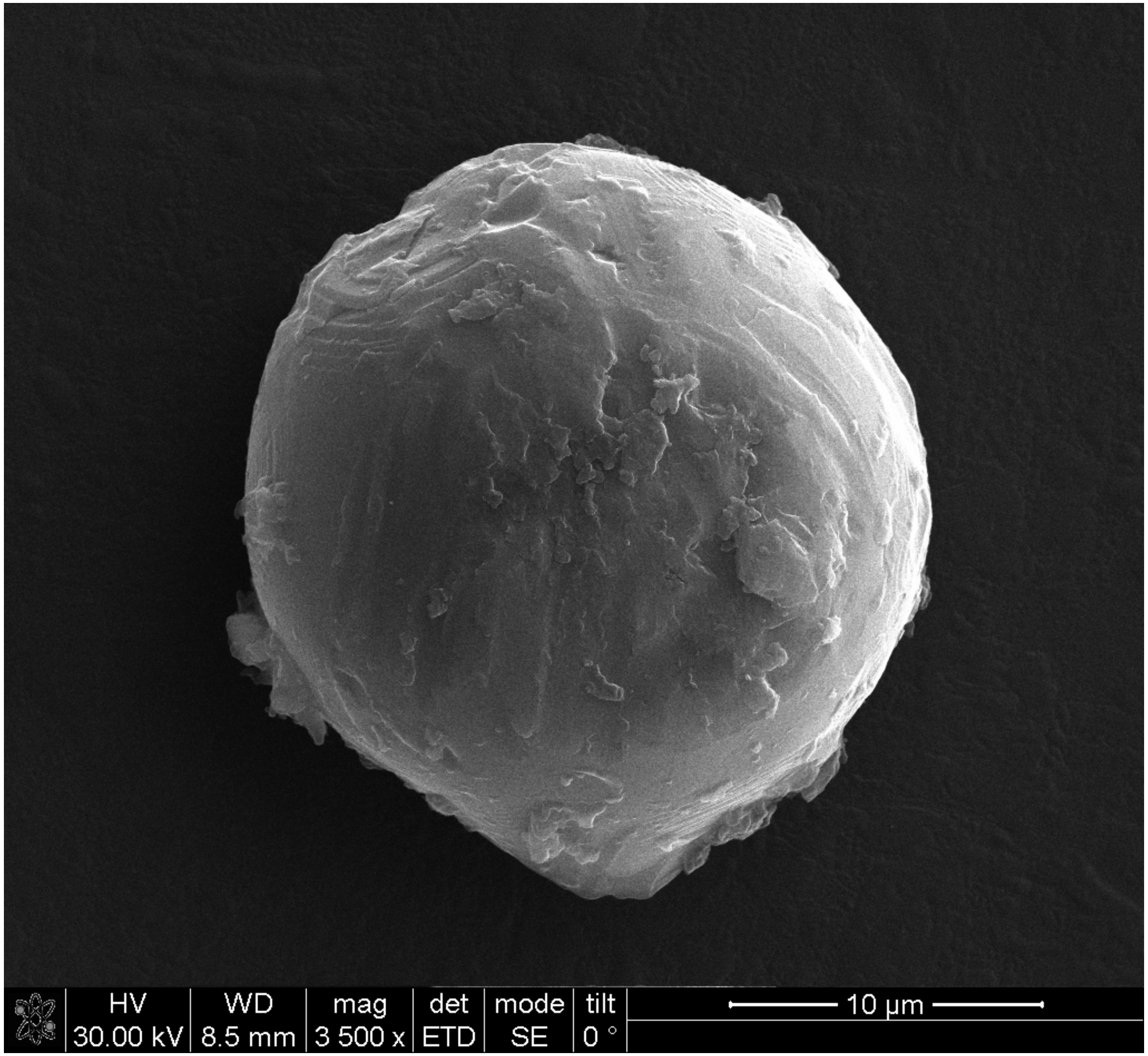




Sub-wavelength dielectric resonators

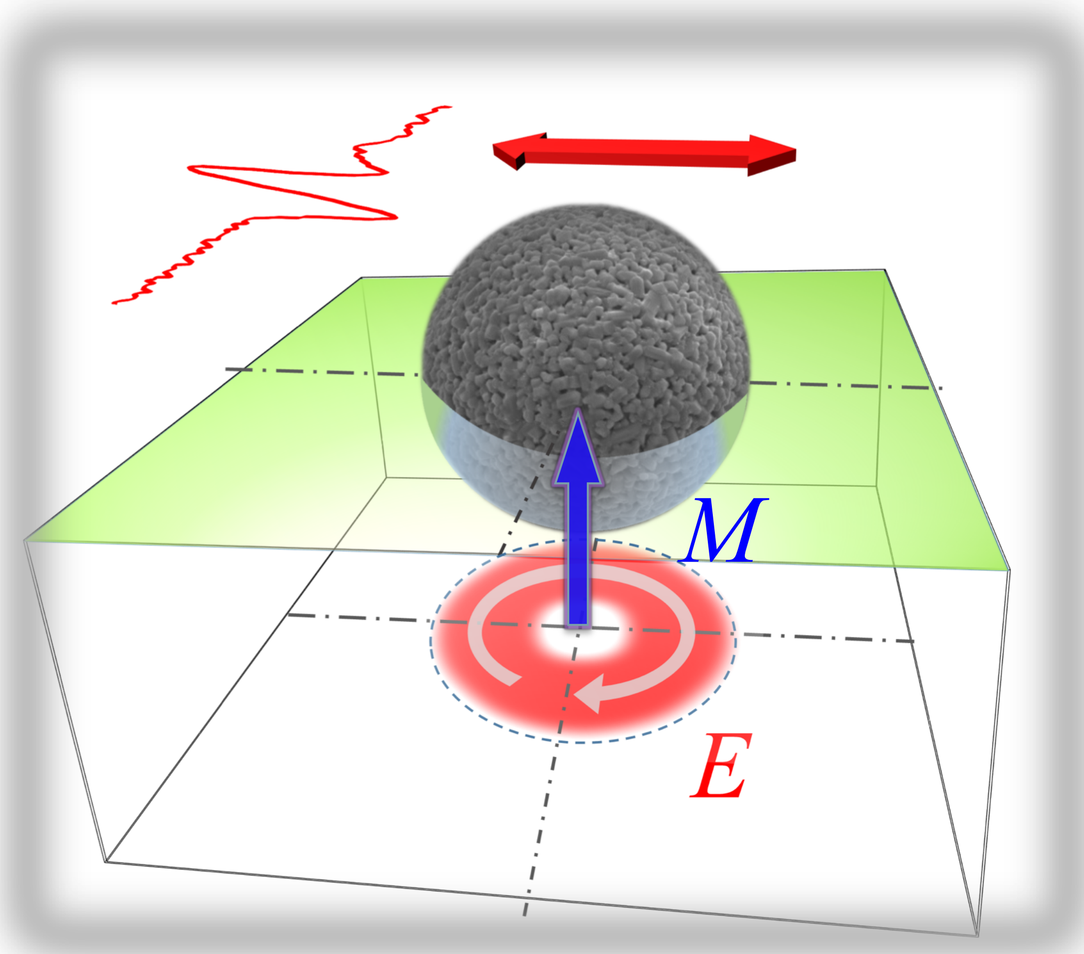
Spectroscopy and mode imaging

High permittivity dielectric resonator



TiO_2 microsphere:
~20 μm diameter

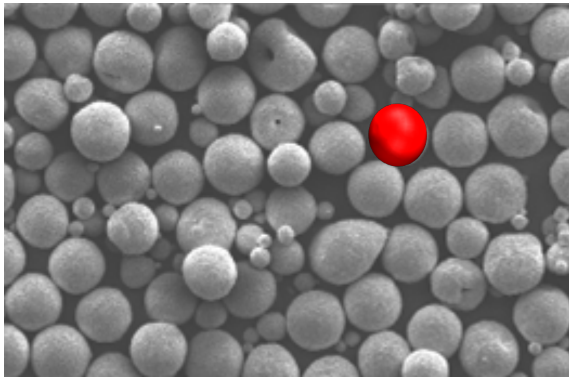
Mie resonances in TiO_2 spheres



Optics Express, 22, 23034 (2014)

Probing of single high-permittivity resonators

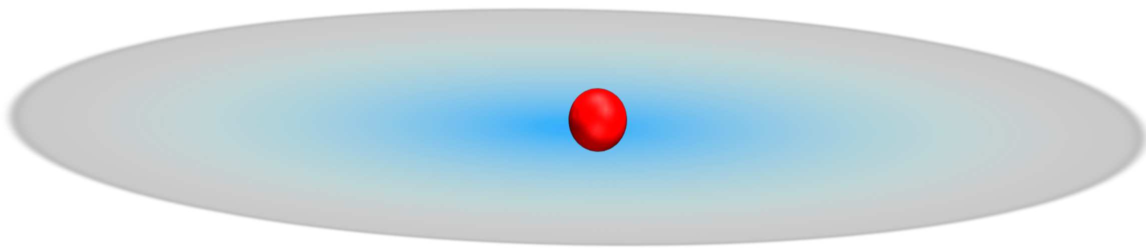
Sub-wavelength size of TiO_2 resonators $d \sim \lambda/n$

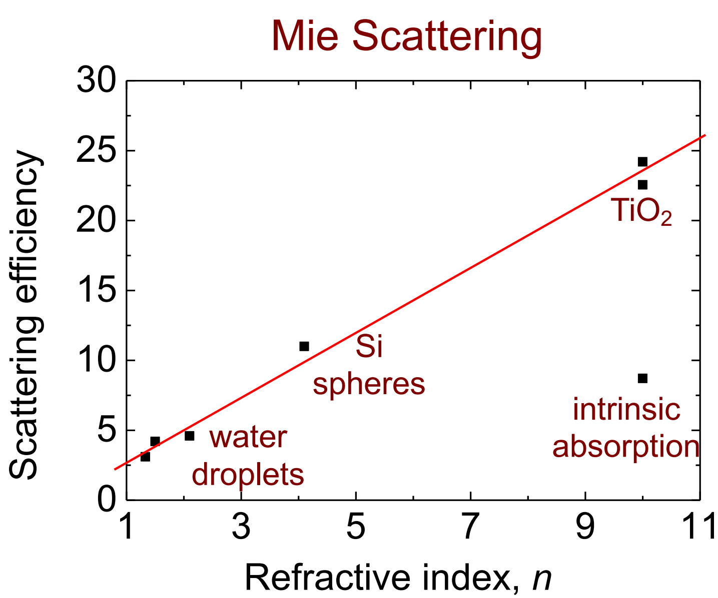


What is the effect of a single sphere?

Probing of single high-permittivity resonators

Sub-wavelength size of TiO_2 resonators $d \sim \lambda/n$





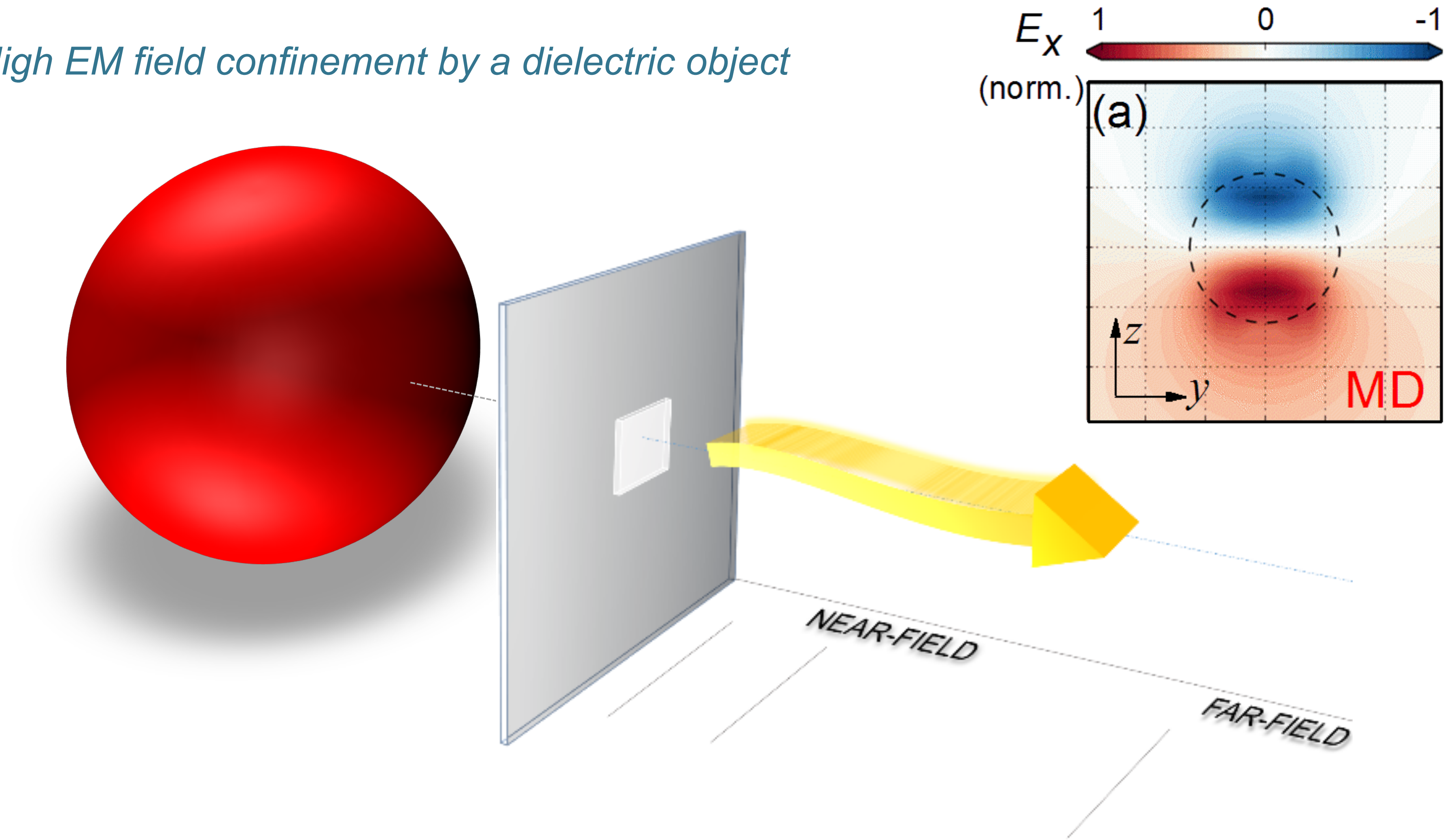
Total scattered power reduces due to the physical cross-section scaling with n^{-2}

Far-field total extinction by a single TiO_2 sphere (est. for typical THz-TDS) :

0.1-1.0%

Effect on sub-wavelength aperture transmission

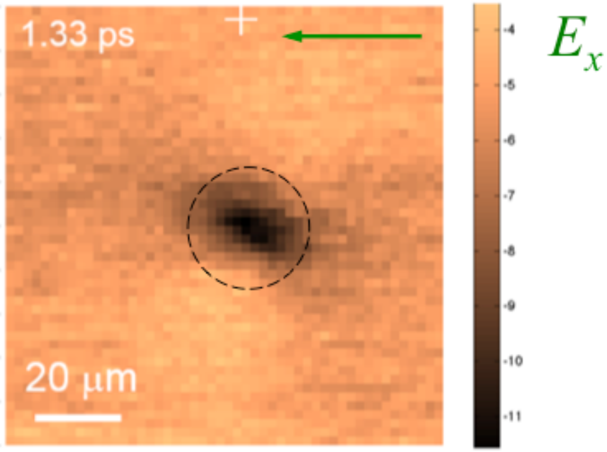
High EM field confinement by a dielectric object



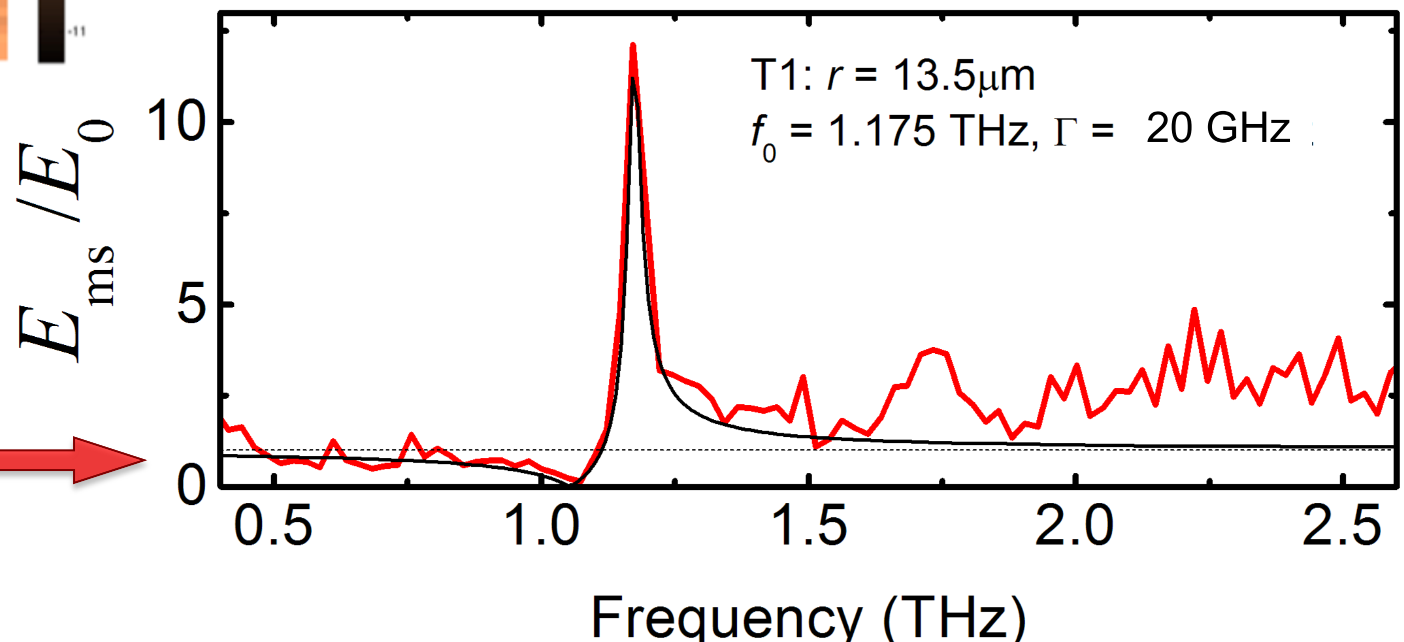
Enhanced transmission through aperture can be used to probe high-ε resonators

Optics Express, 22, 23034 (2014)

Spectroscopic signature of the MD and ED resonances



Enhancement factor and width to quantify the resonator

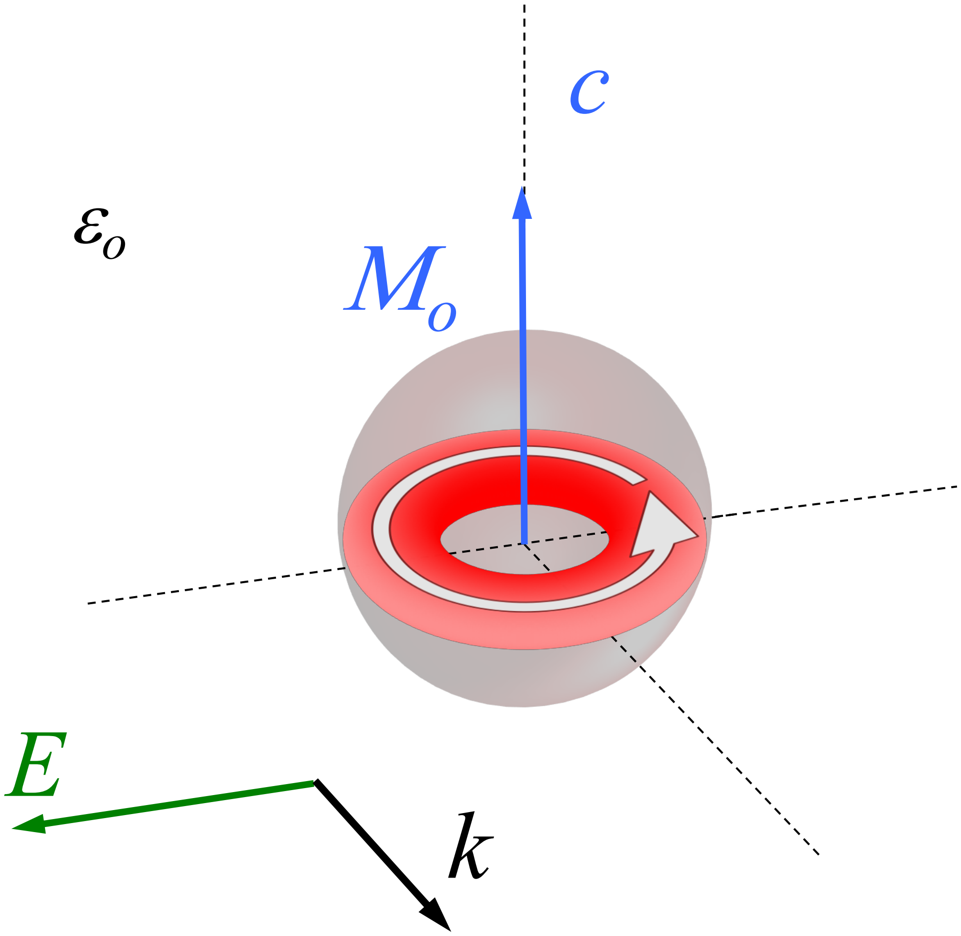


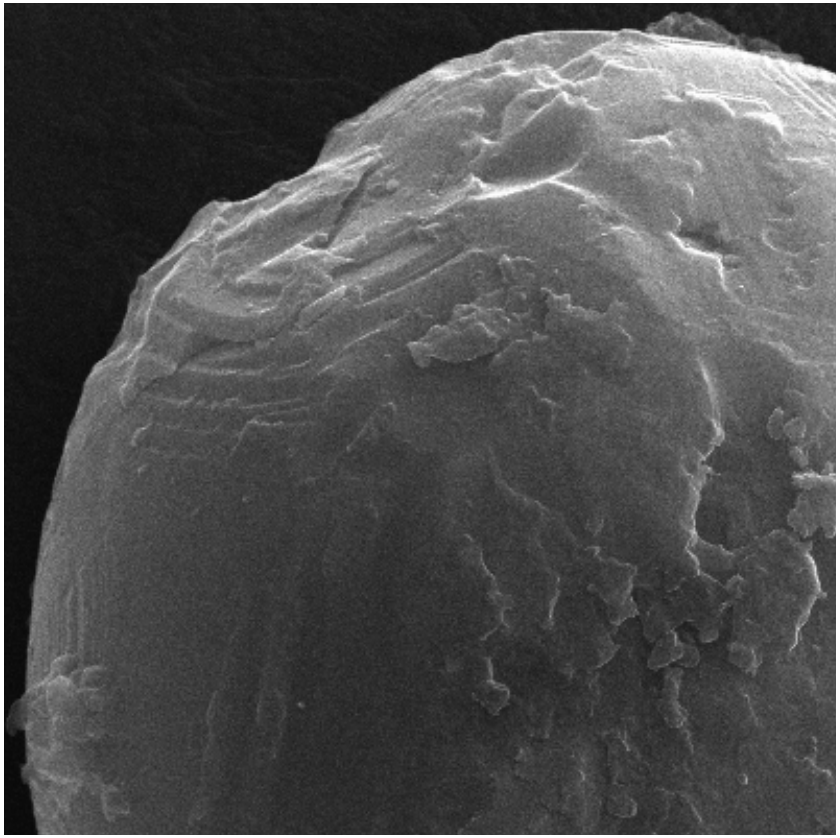
No effect on transmission away from resonance

Interference minimum (Fano line-shape)

Anisotropy

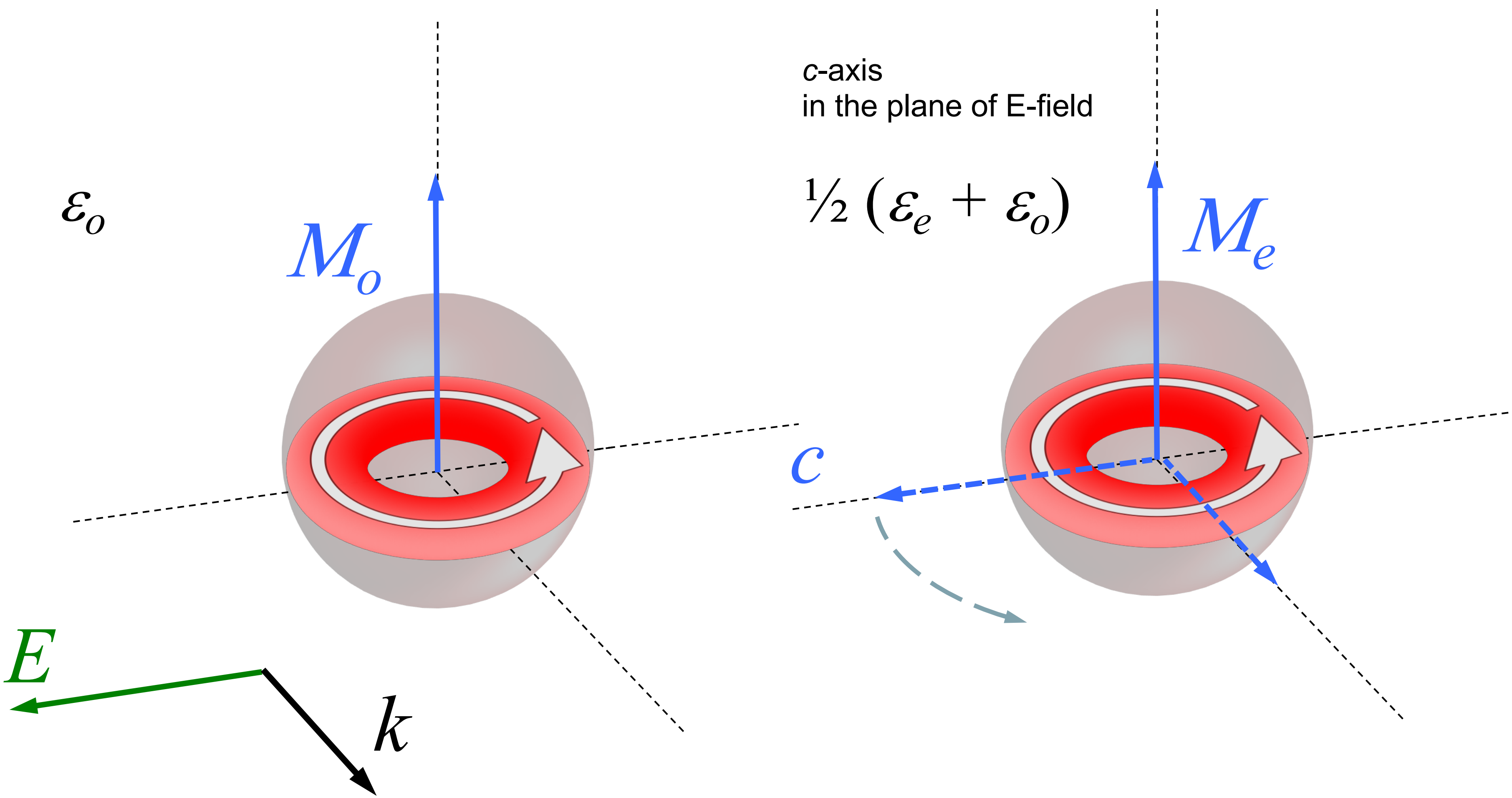
TiO_2: $\varepsilon_e = \sim 150$; $\varepsilon_o = \sim 70$



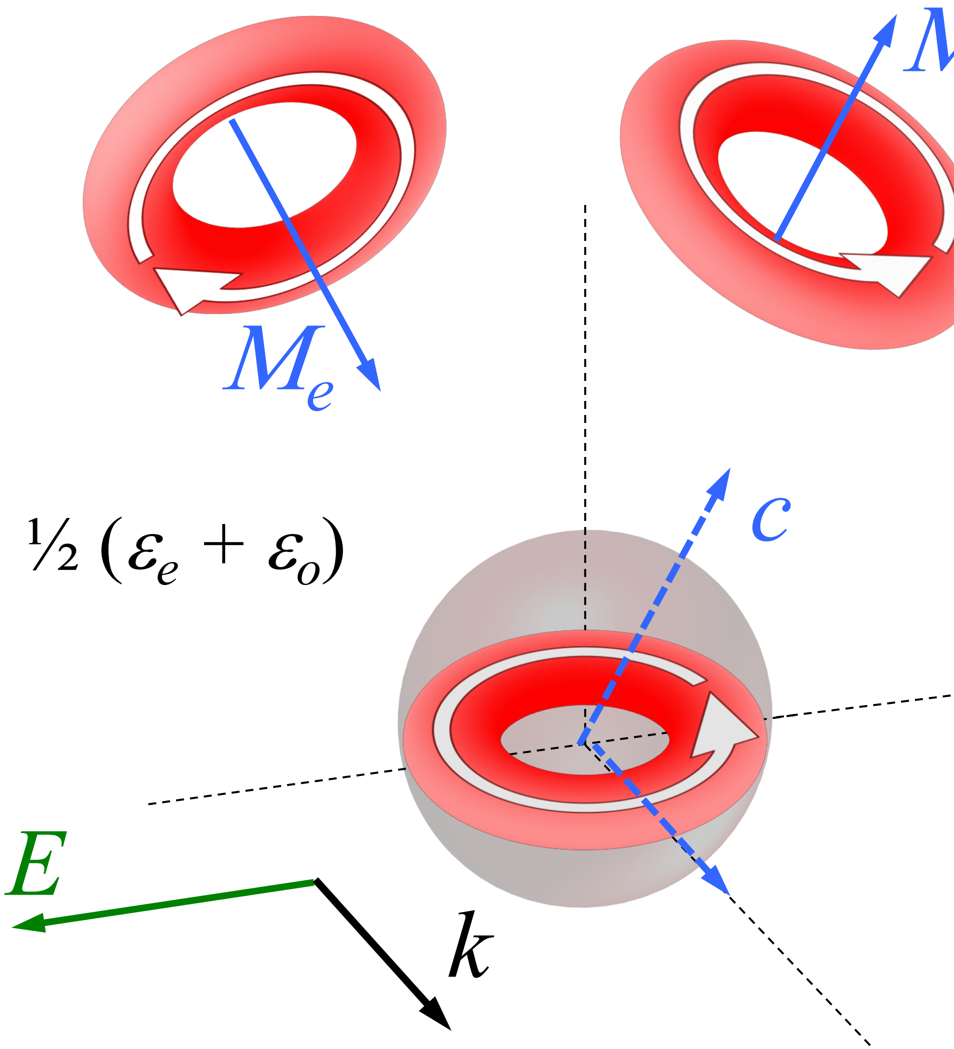


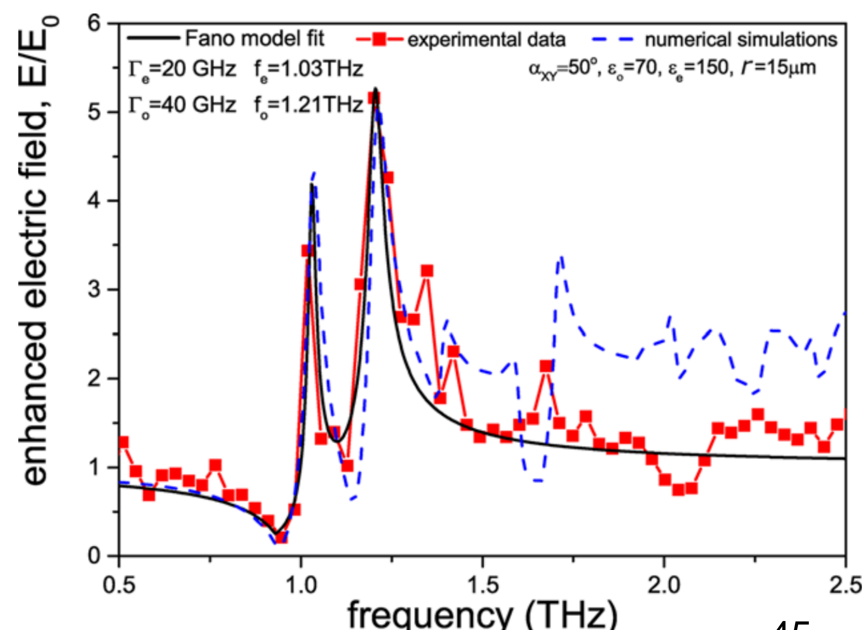
Anisotropy

TiO_2: $\varepsilon_e = \sim 150; \;\; \varepsilon_o = \sim 70$

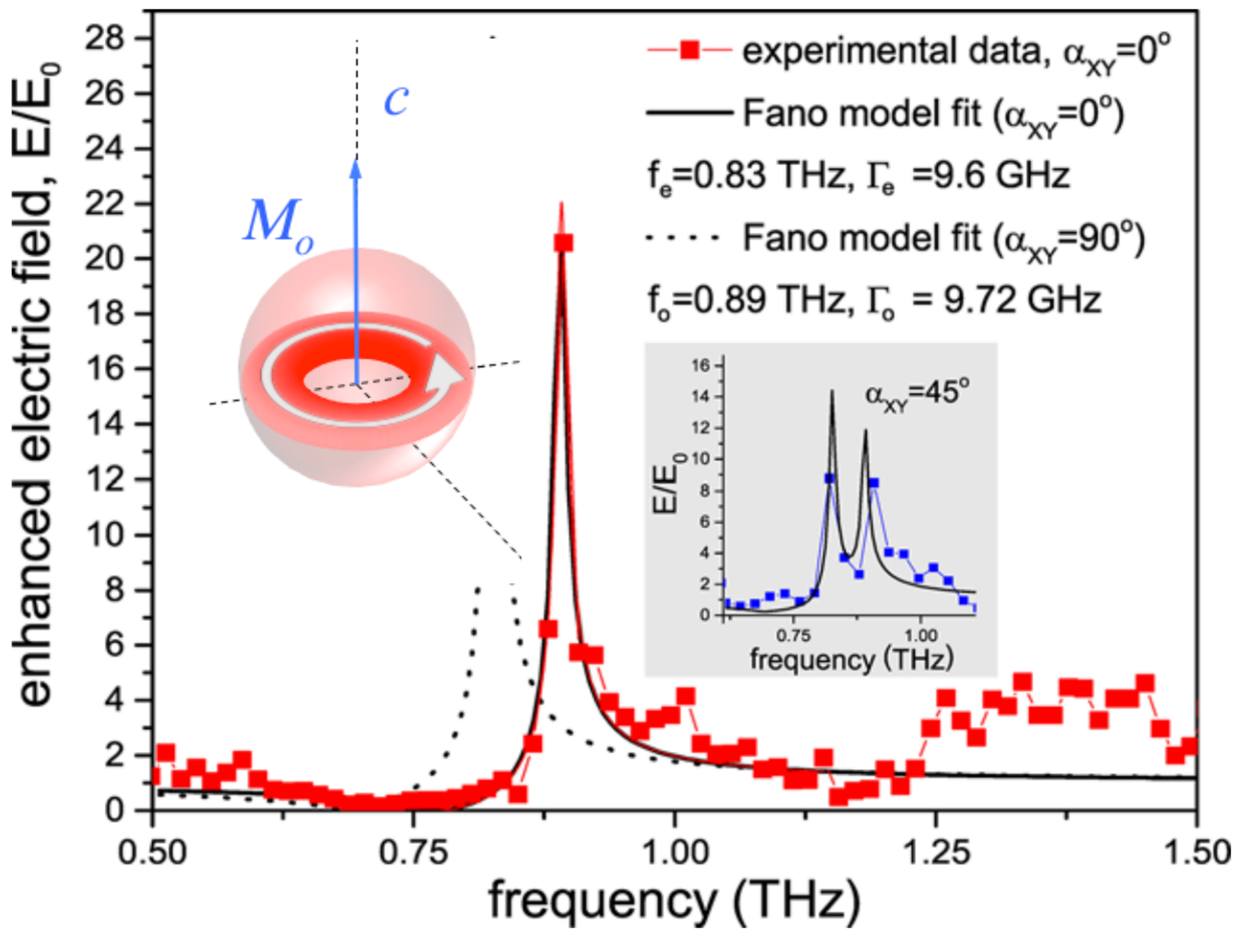


TiO_2: $\varepsilon_e = \sim 150$; $\varepsilon_o = \sim 70$



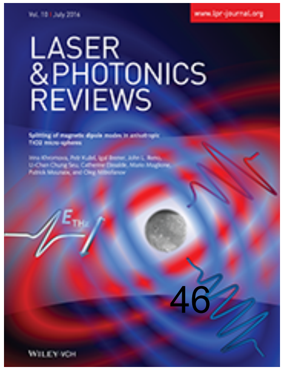


MD in TiO_2 spheres

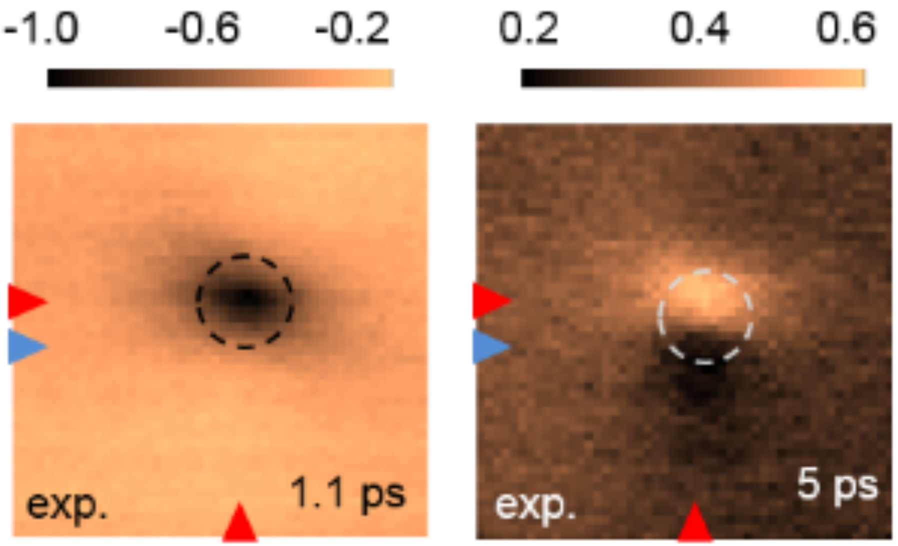


Near-field spectroscopy allows 'seeing' both modes

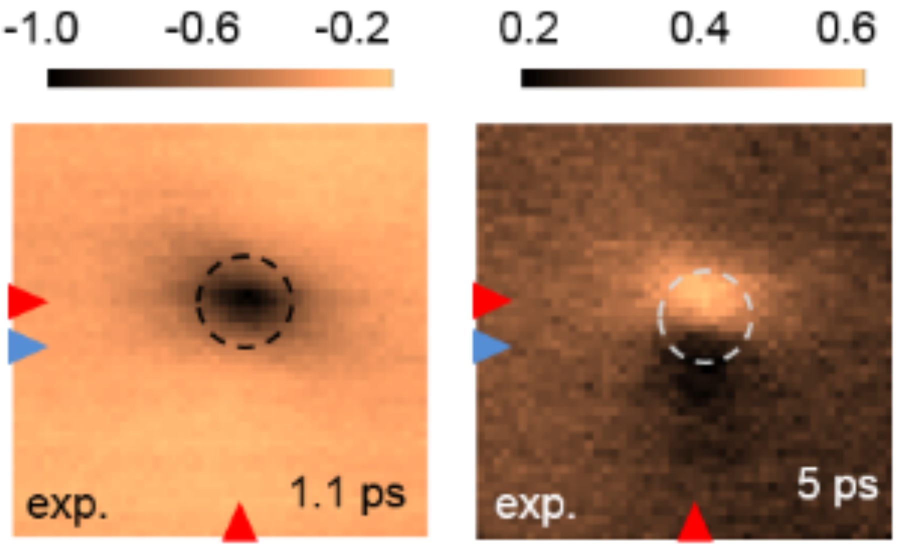
I. Khromova et al., *Laser and Photon. Reviews* (2016)

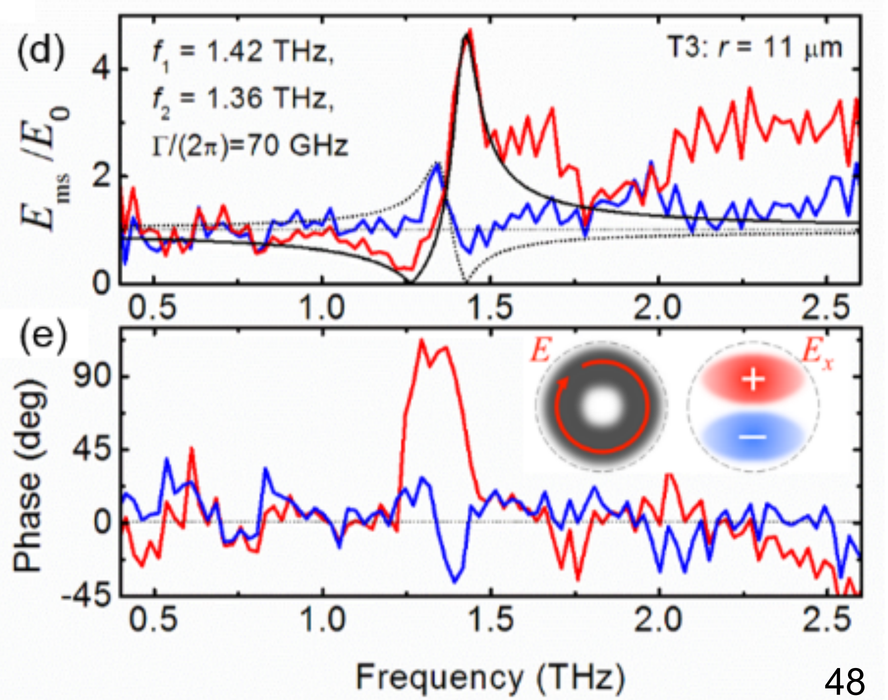


Non-sphericity

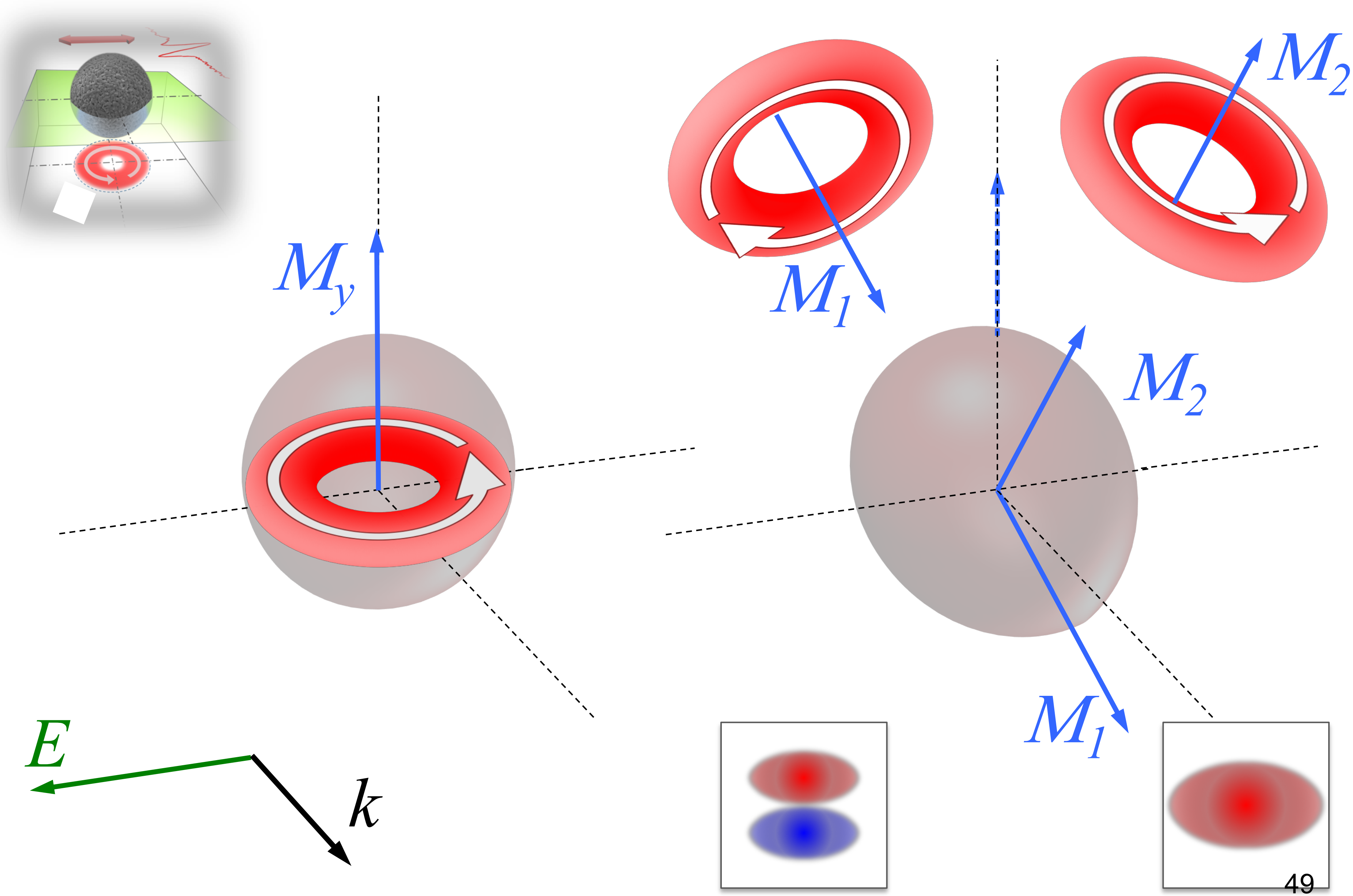


Non-sphericity

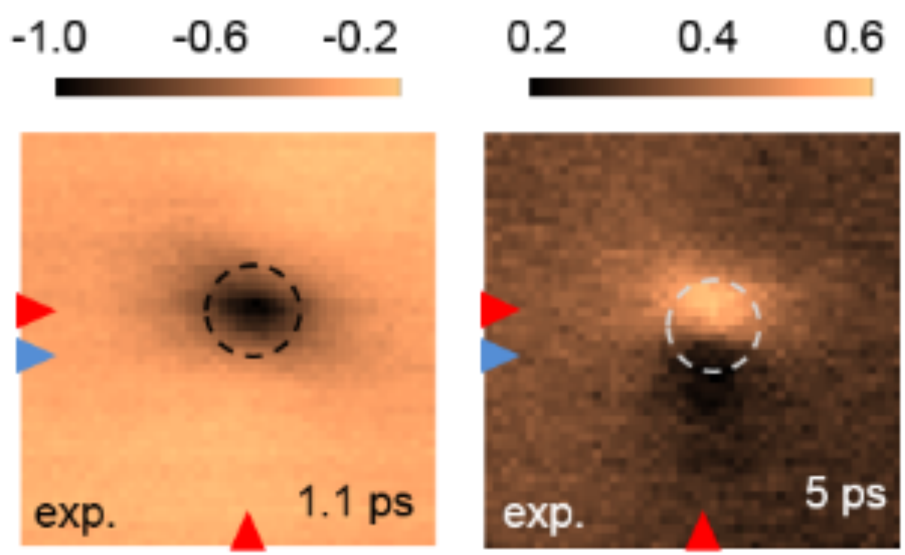


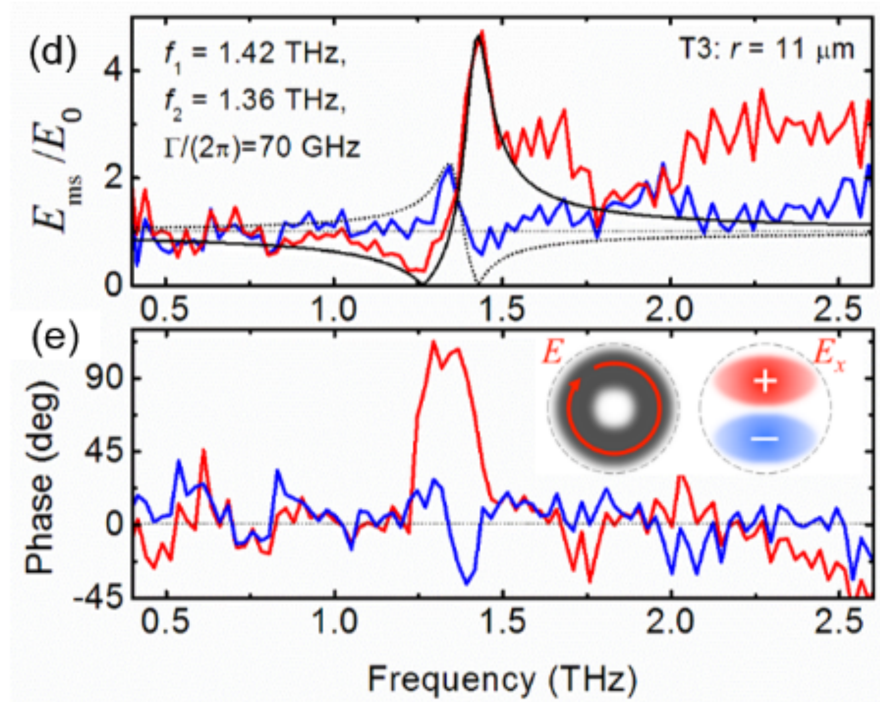


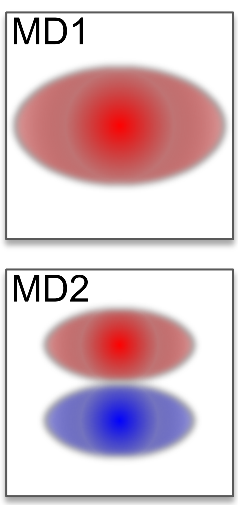
Non-sphericity

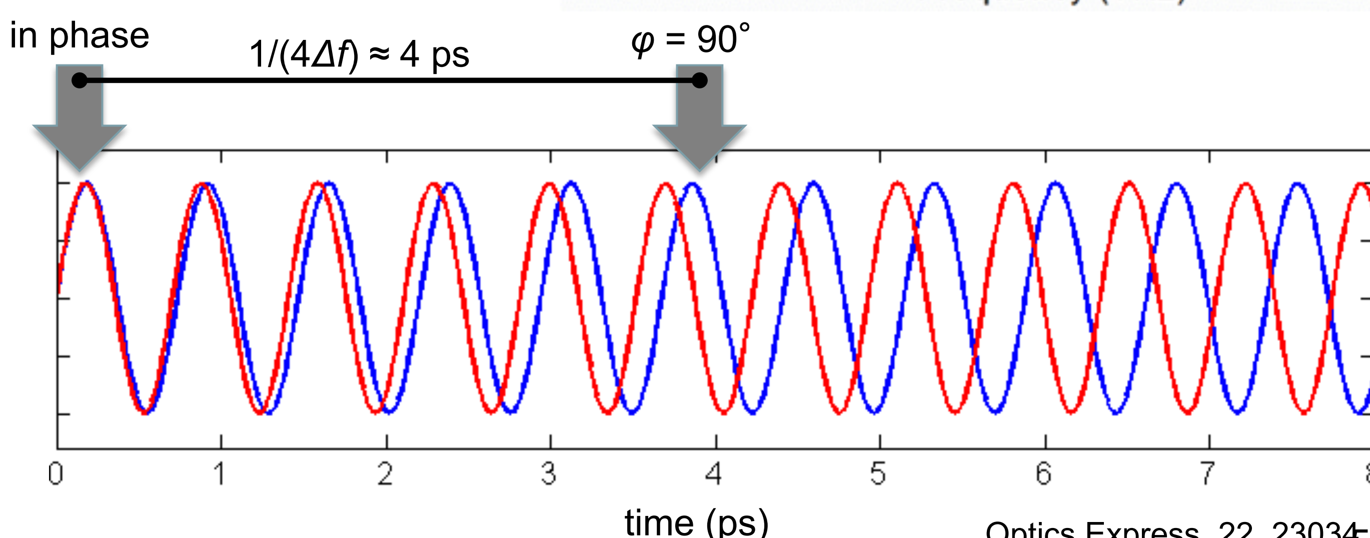


Non-sphericity







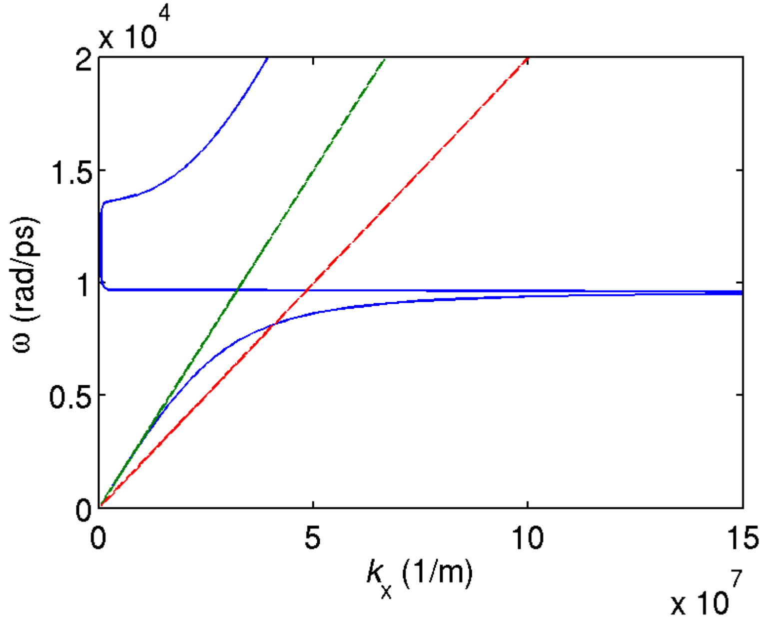


Optics Express, 22, 23034 (2014)

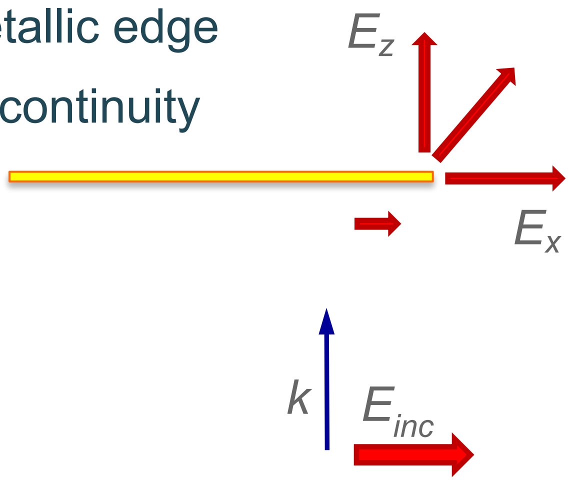
Plasmonic resonators and surface waves

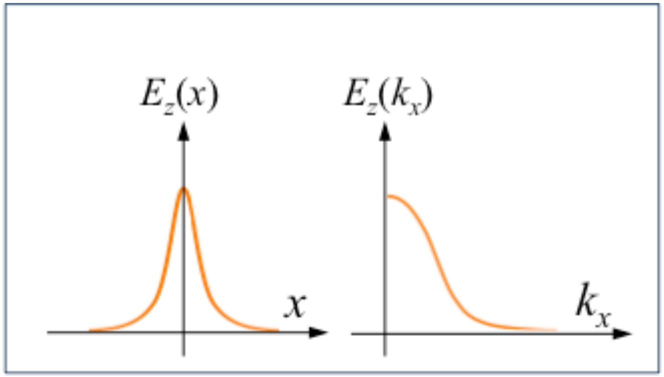
Spectroscopy and mode imaging

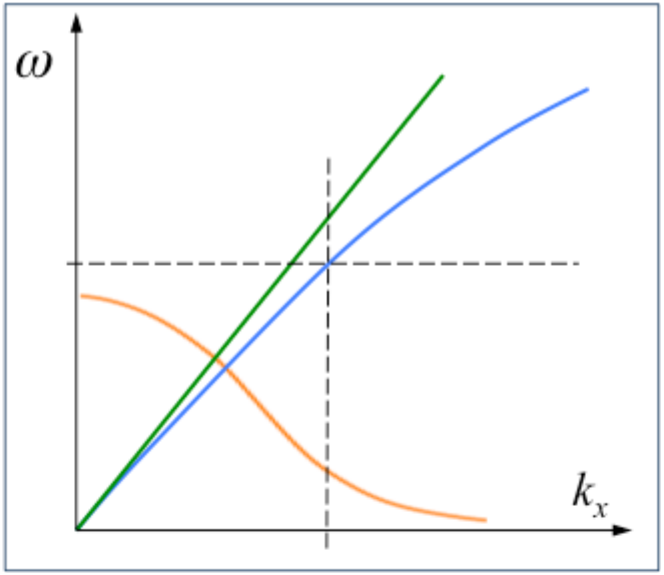
Broadband excitation of surface plasmon waves



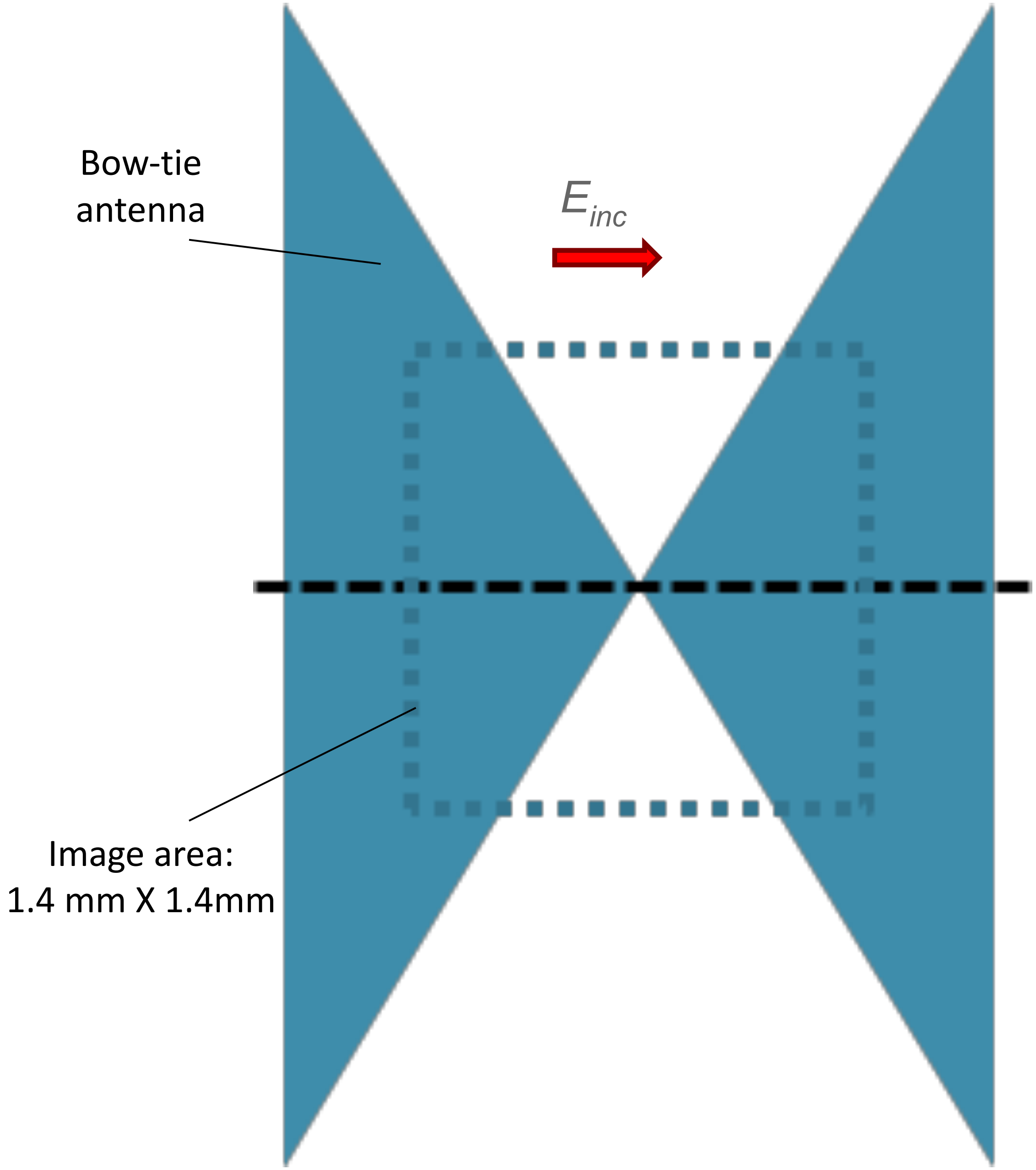
Metallic edge discontinuity





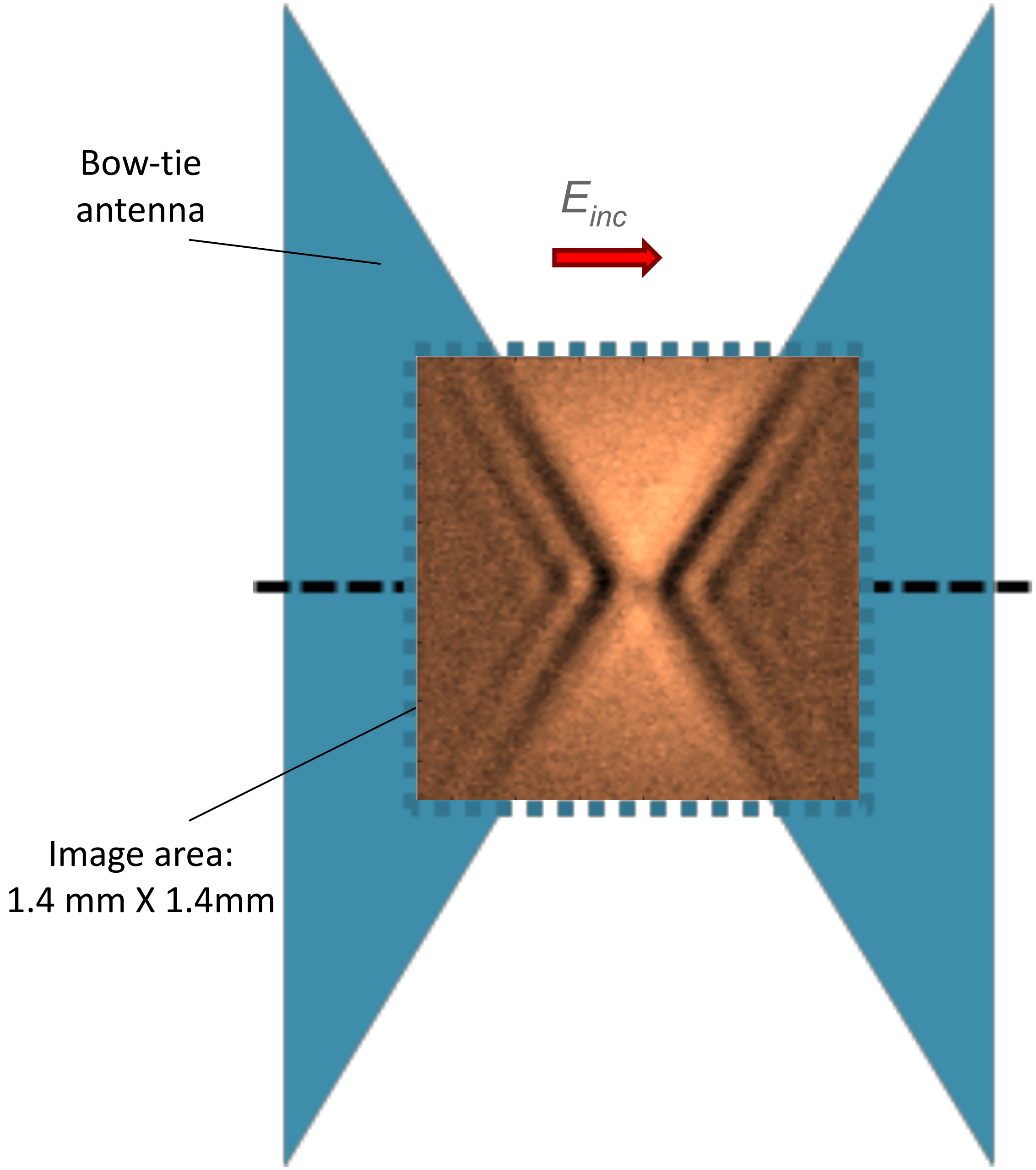


Generation of surface waves at metallic edges



Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

Generation of surface waves at metallic edges



Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

Generation of surface waves at metallic edges

Bow-tie antenna

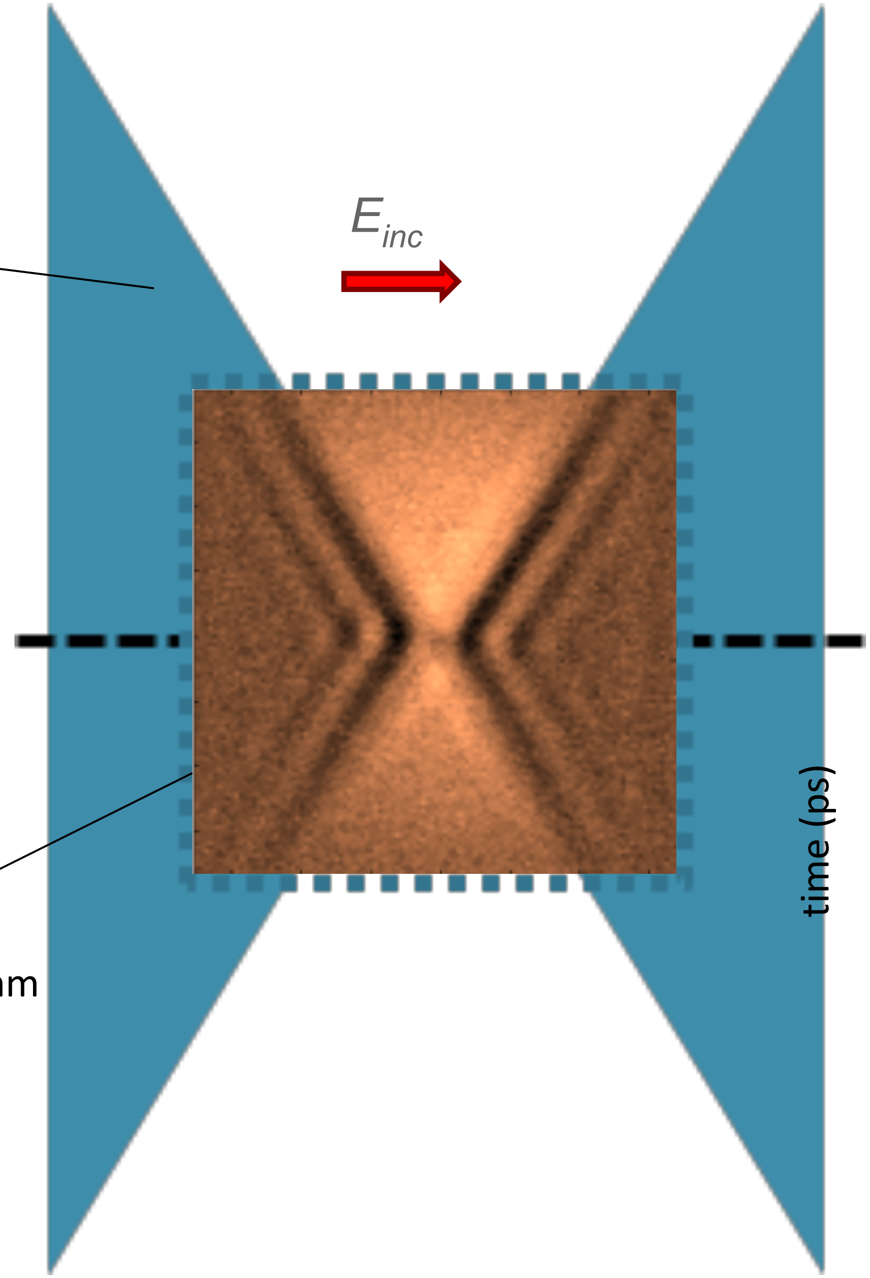
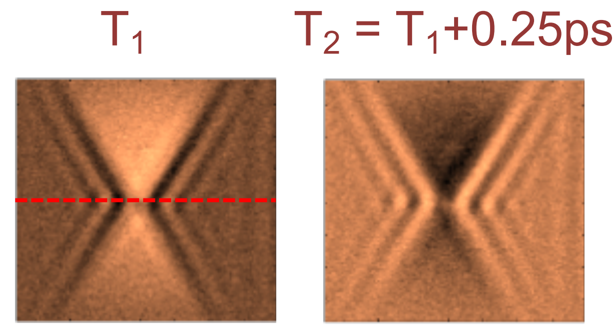
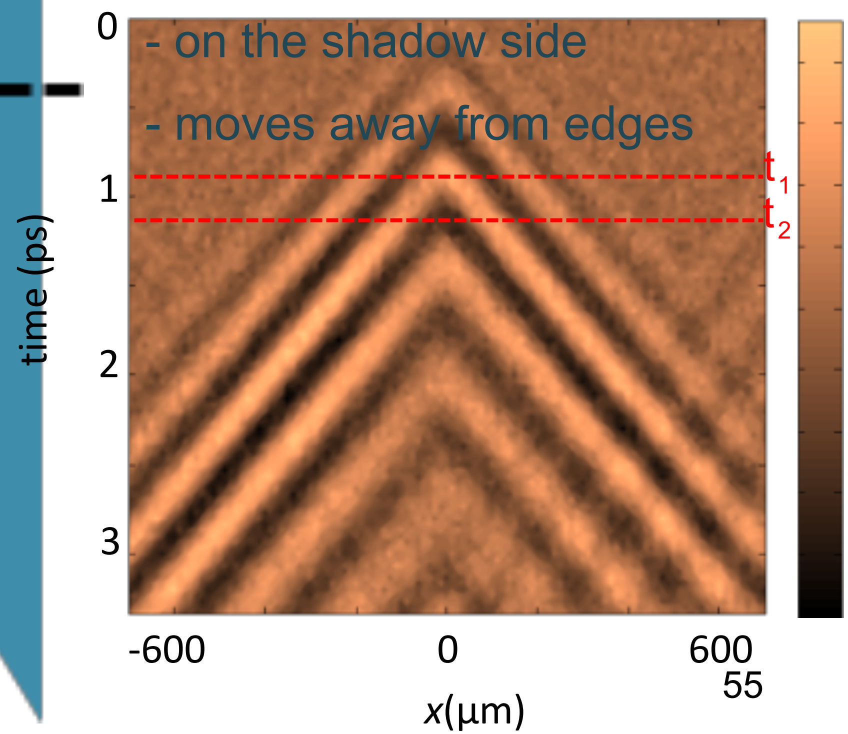


Image area:
1.4 mm X 1.4mm



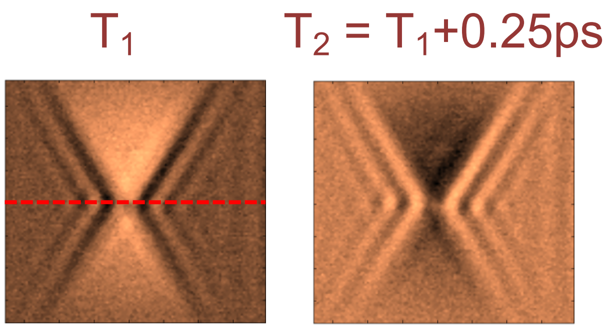
Distinctive signature of the THz wav

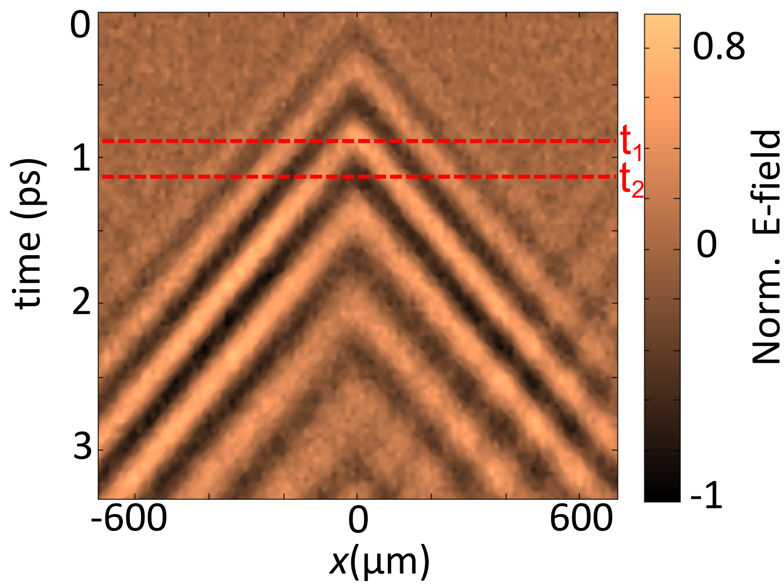
- on the shadow side
- moves away from edges

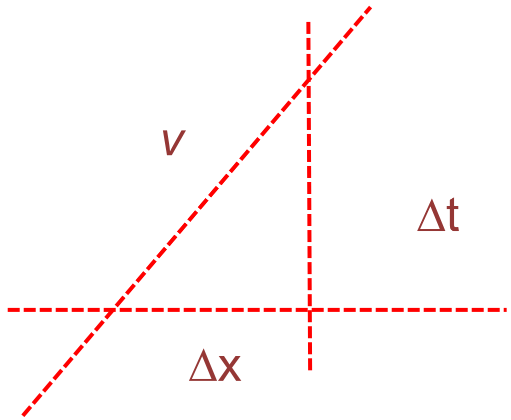


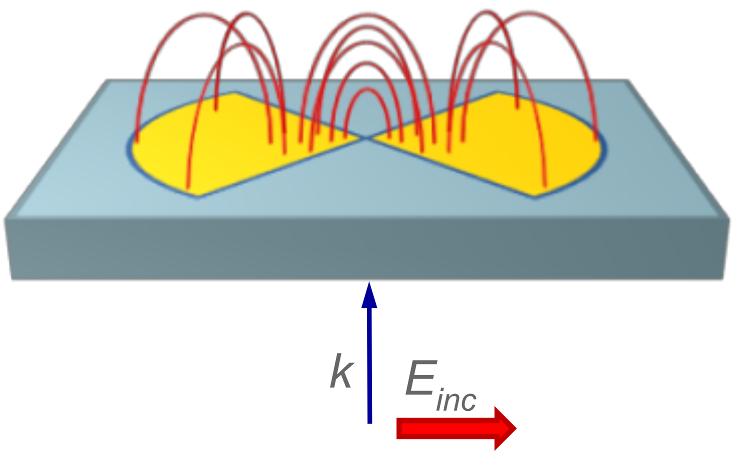
Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

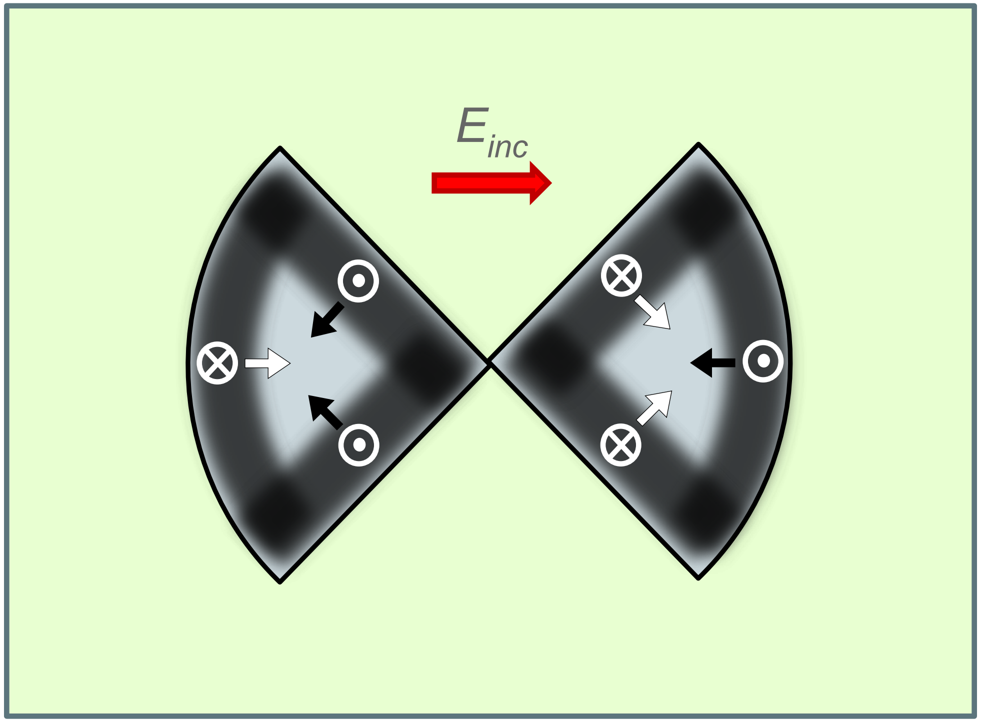
THz surface waves



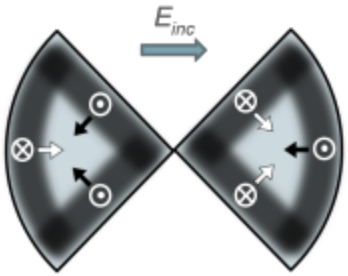




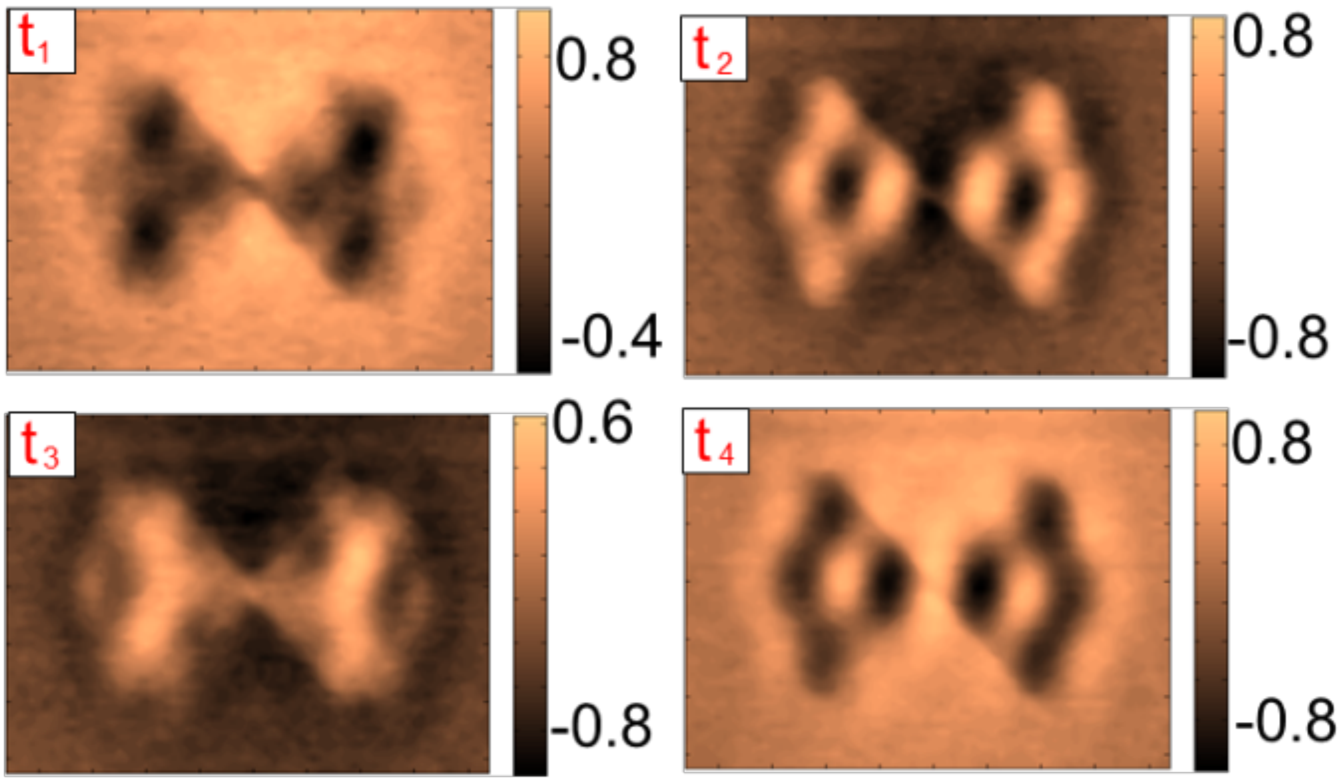

k
E_{inc}


E_{inc}

Experimental SPP patterns

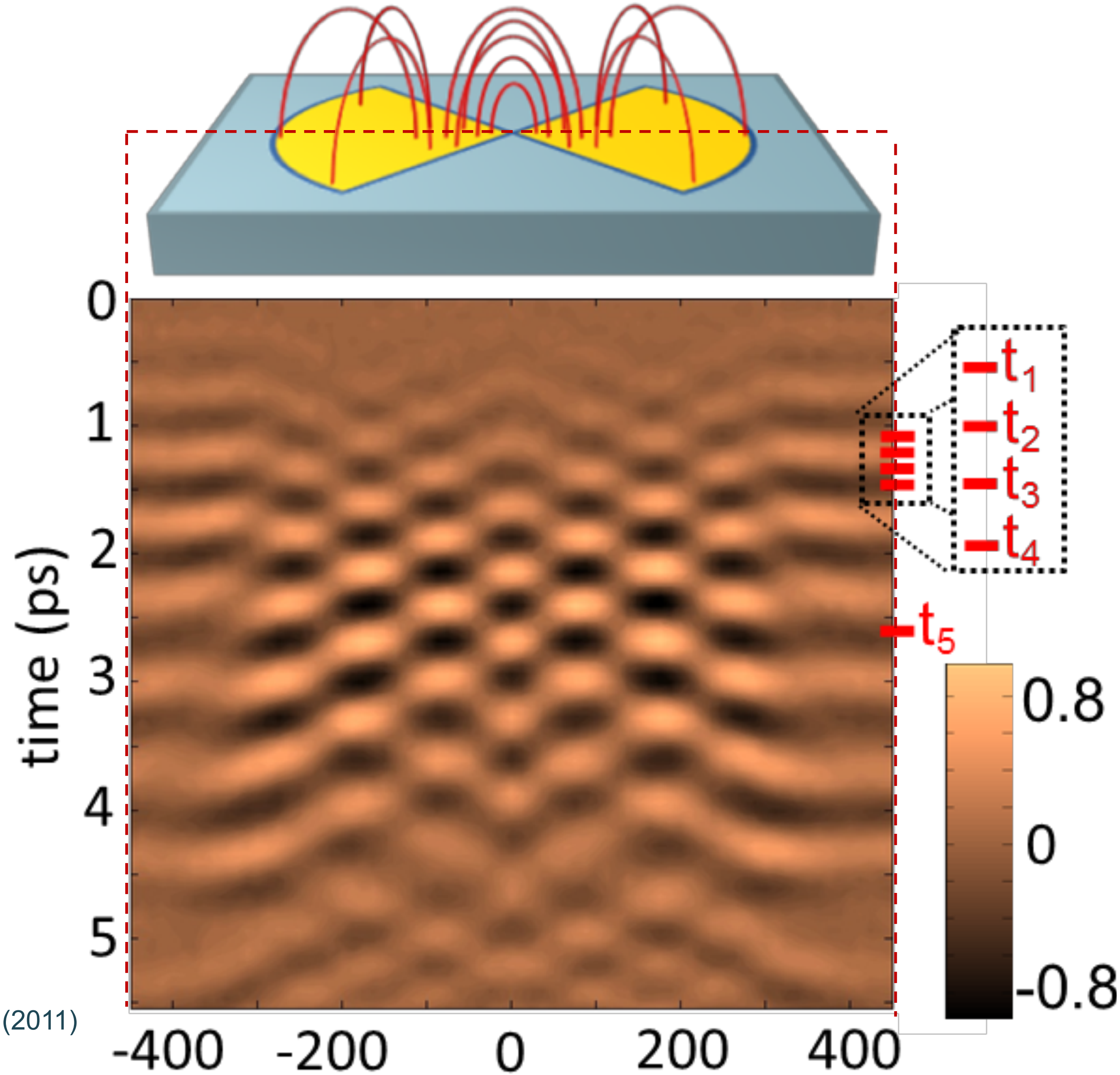


Consecutive images ("frames") ~0.13 picosecond apart



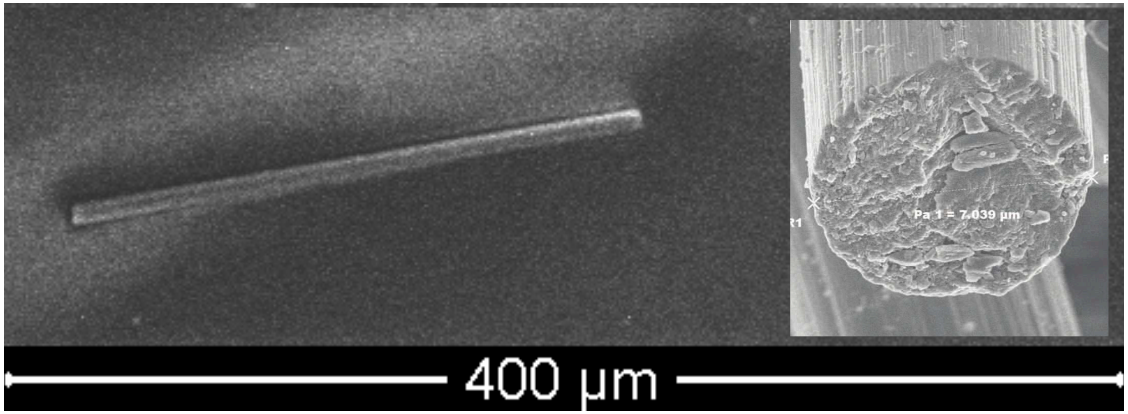
Mueckstein *et al.*, J.of IRMMW 32, 1031 (2011)

SPP resonance on the bow-tie surface



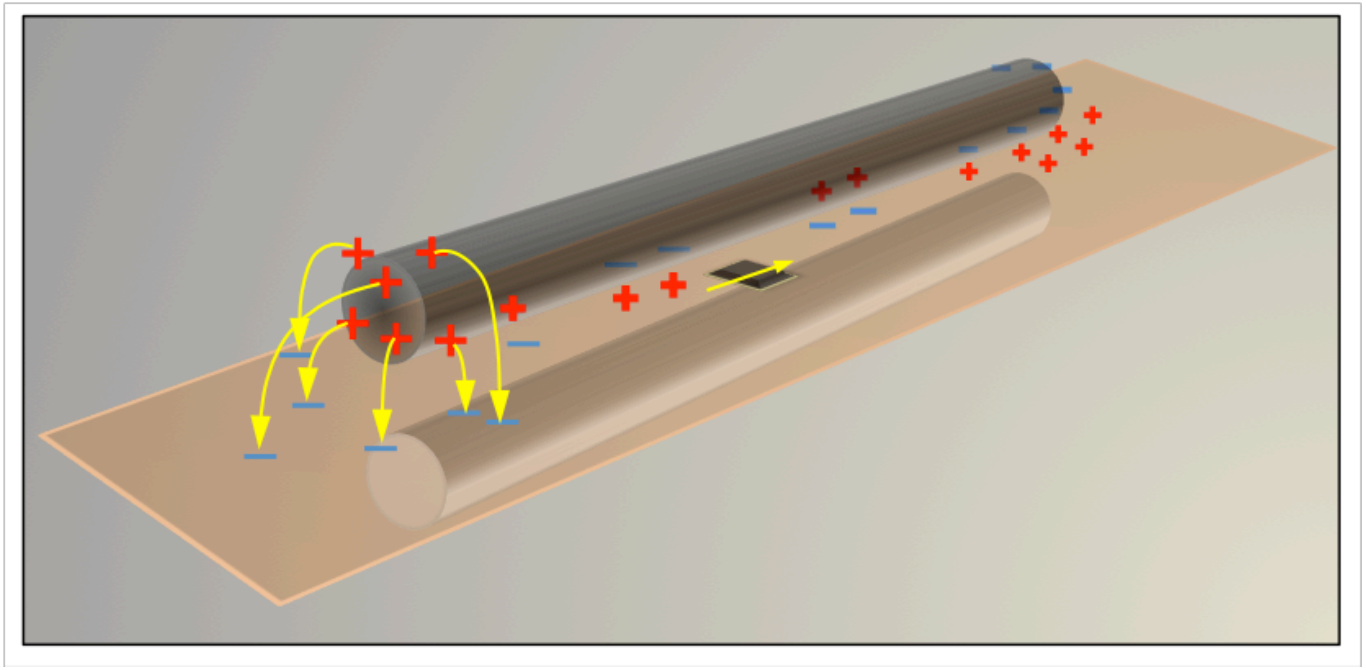
Mueckstein *et al.*,
J.of IRMMW 32, 1031 (2011)

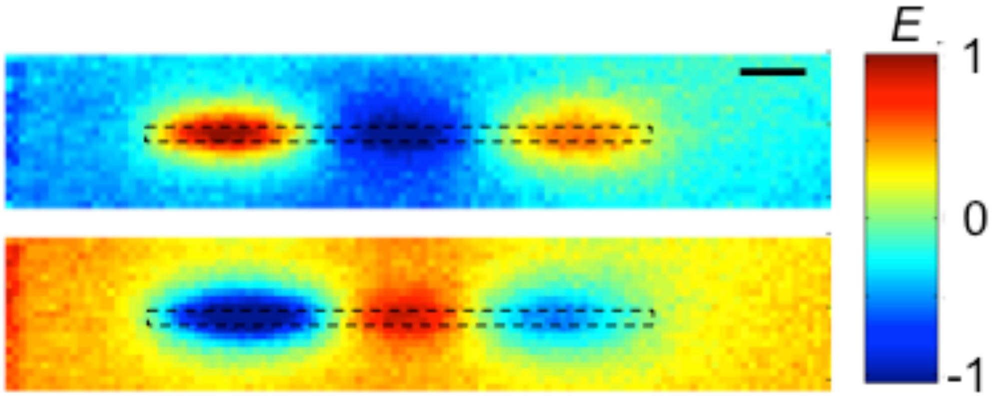
Plasmonic antenna



Conductive carbon fibres:
6.5 μm diameter, 50-250 μm long

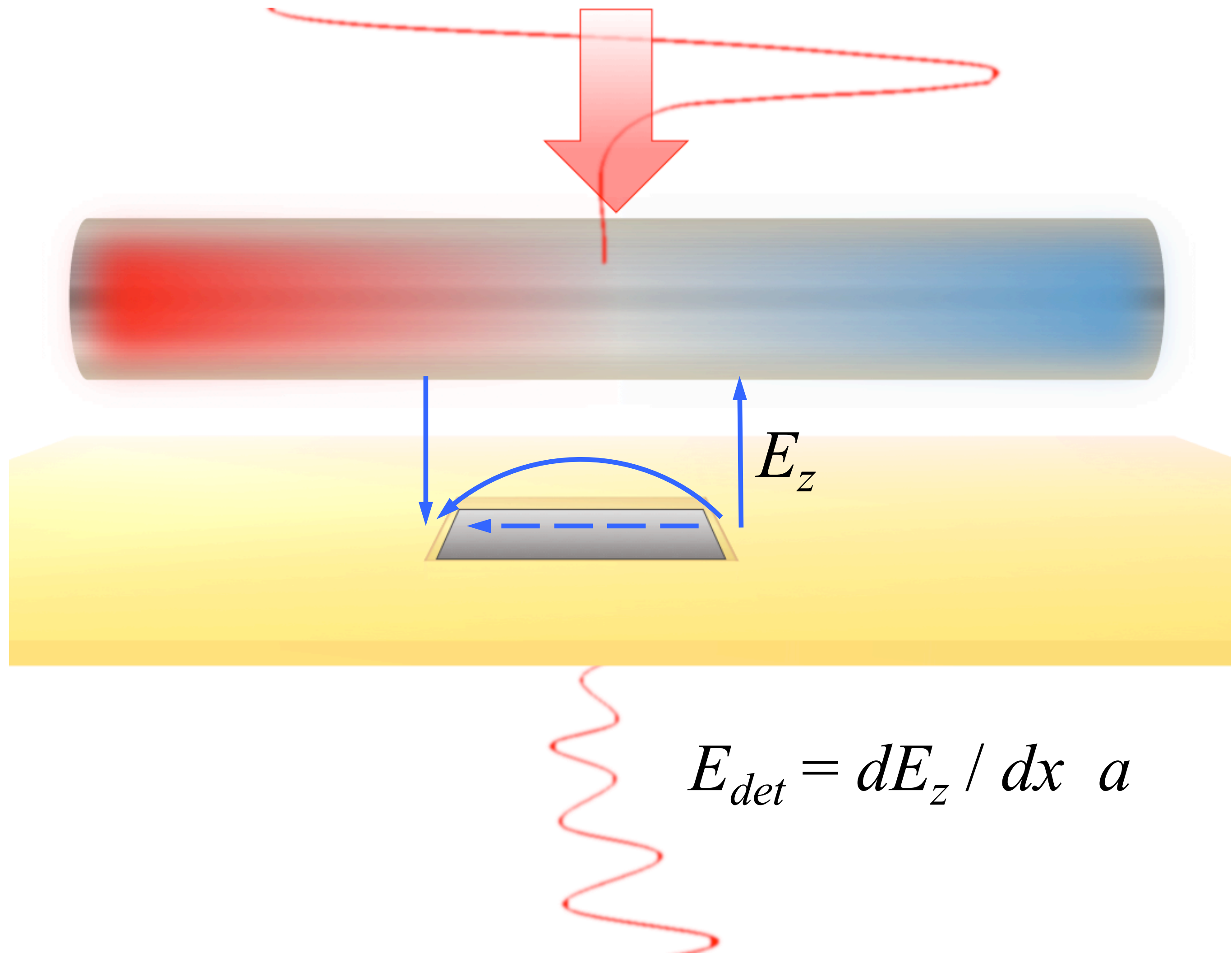
Plasmonic excitations in carbon fibers





IEEE Trans. THz S&T 6, 382 (2016)

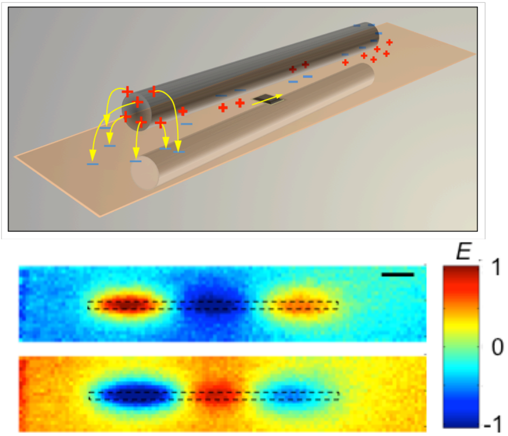
Field detected through the aperture

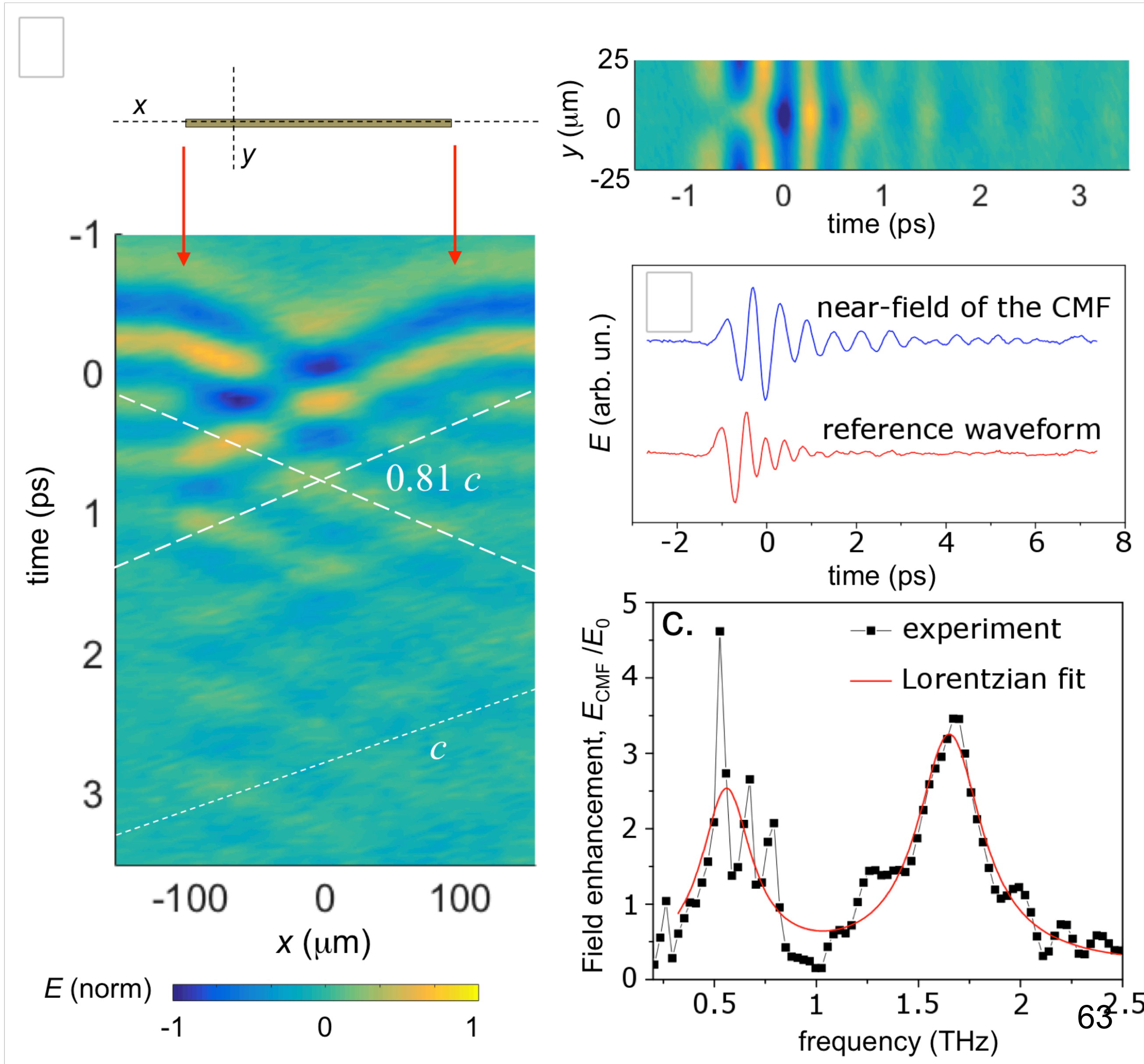


$$E_{det} = dE_z / dx \ \ a$$

Symmetry changes from anti-symmetric to symmetric

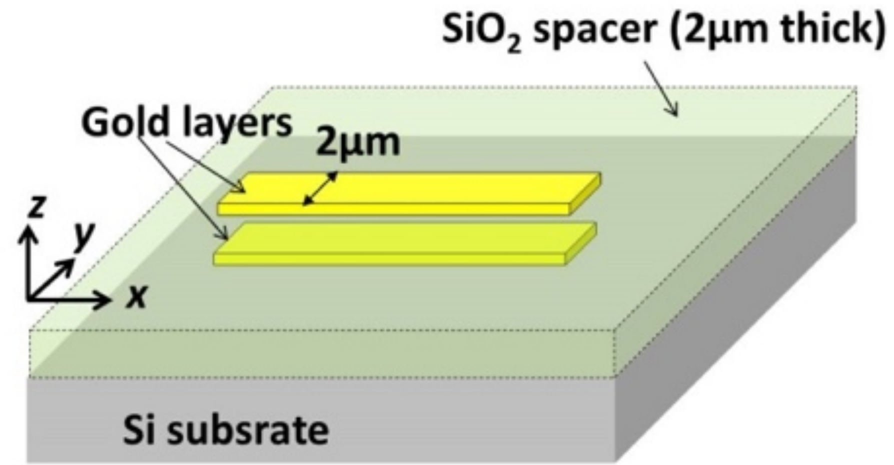
Plasmonic excitations and THz spectroscopy

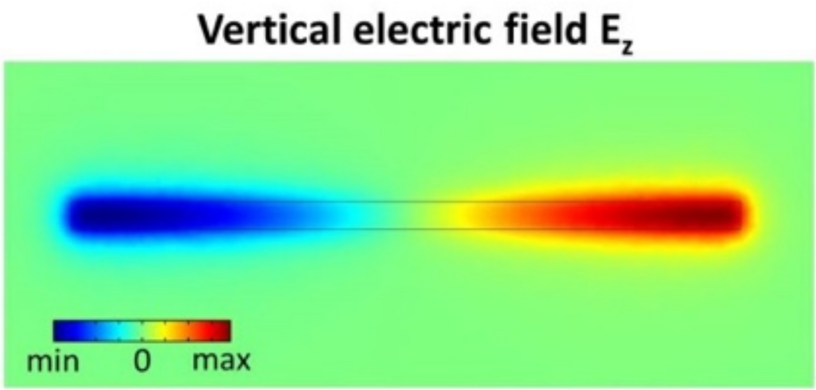


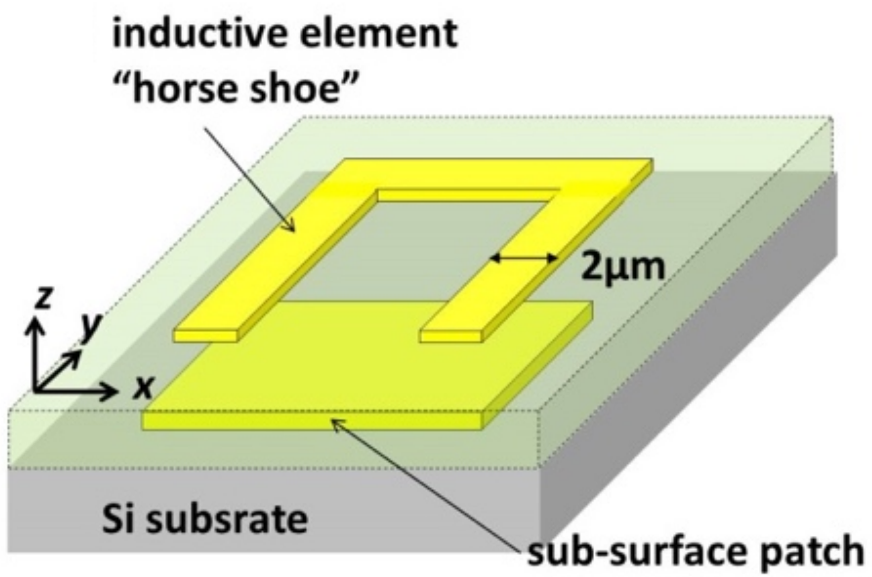


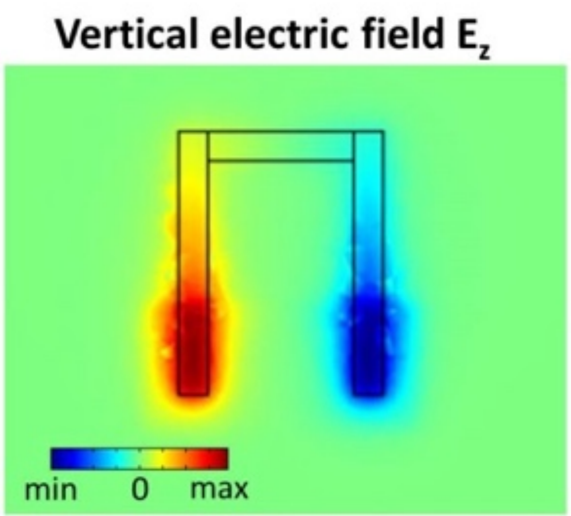
IEEE Trans. THz S&T 6, 382 (2016)

Double-metal resonators

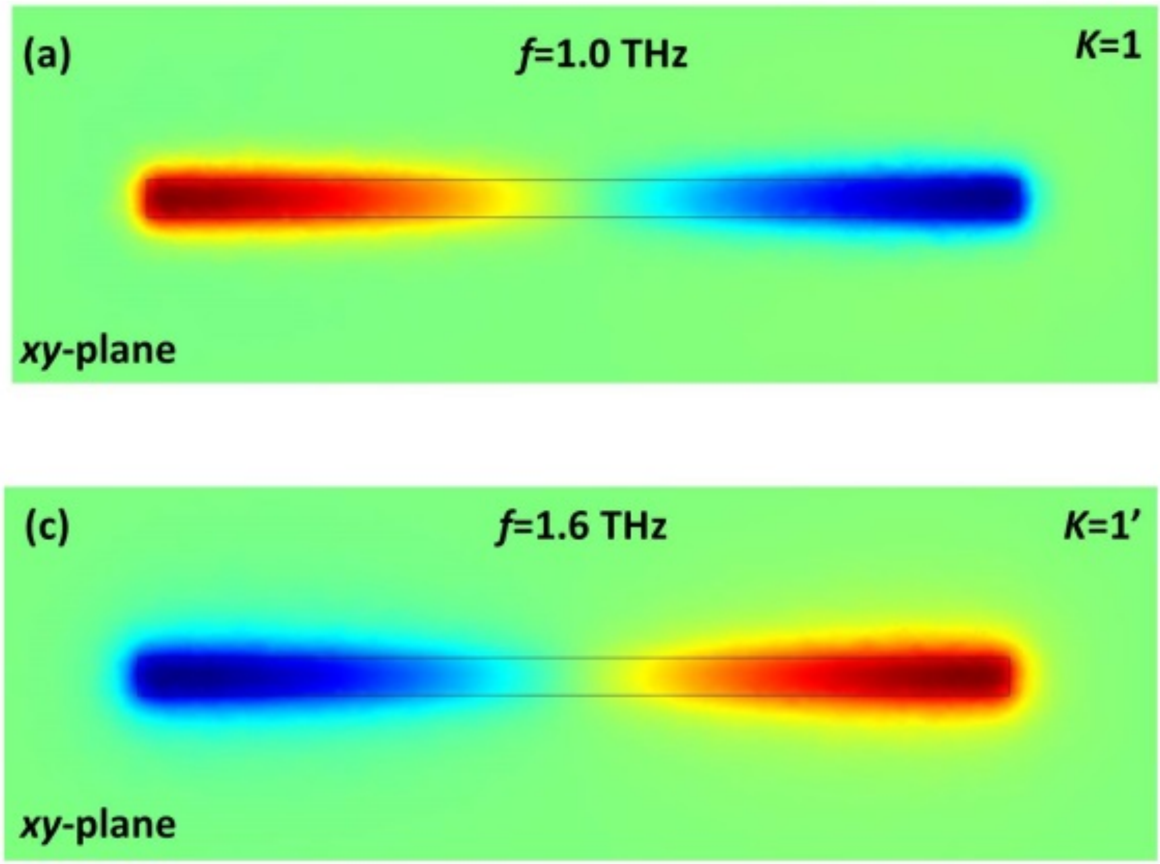






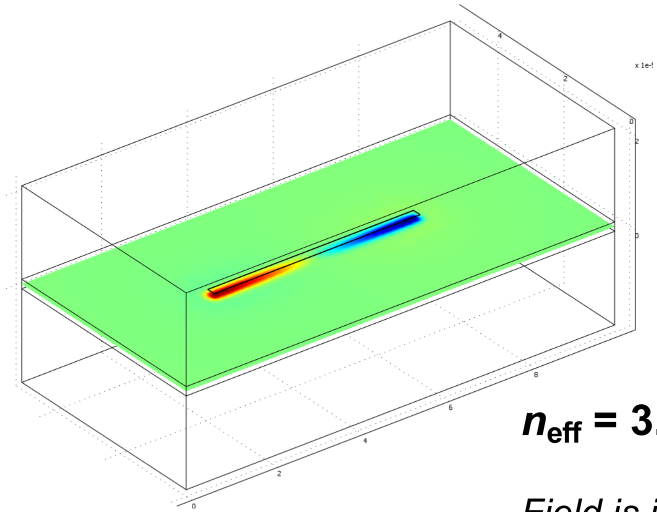


‘Double-metal’ antenna



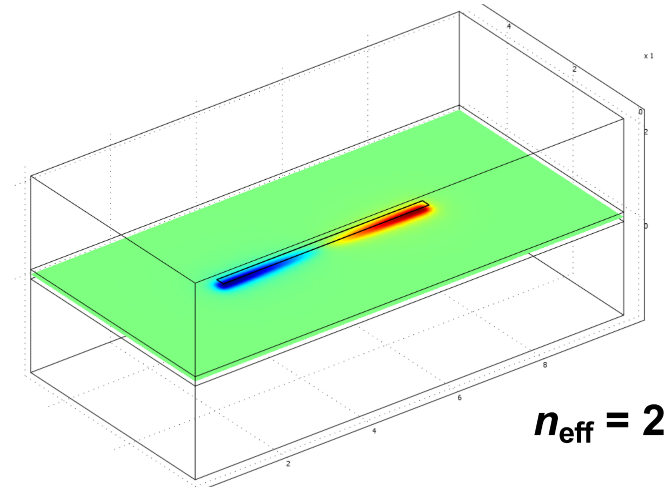
EM simulations reveal two modes with identical field distribution but at different frequencies…

Two modes with the same spatial distribution



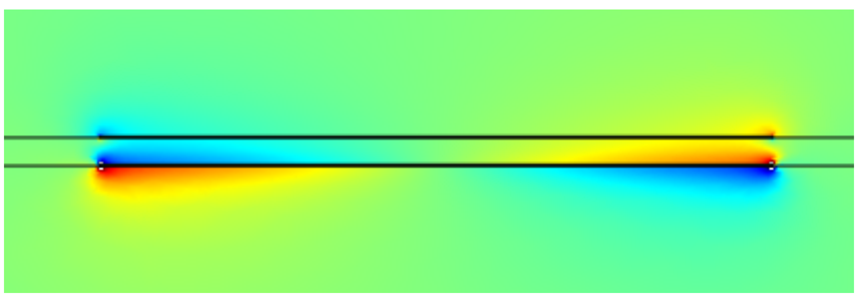
n_{eff} = 3.1

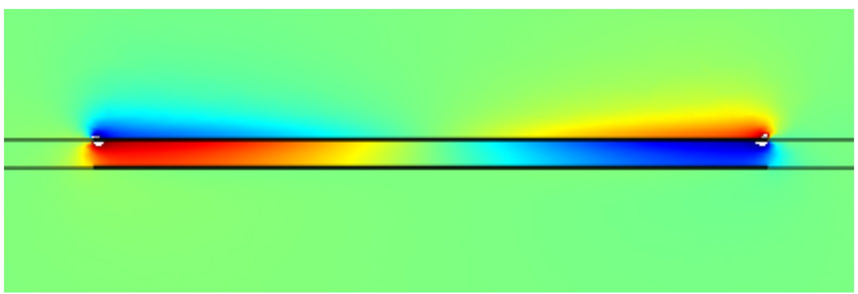
Field is in high index substrate



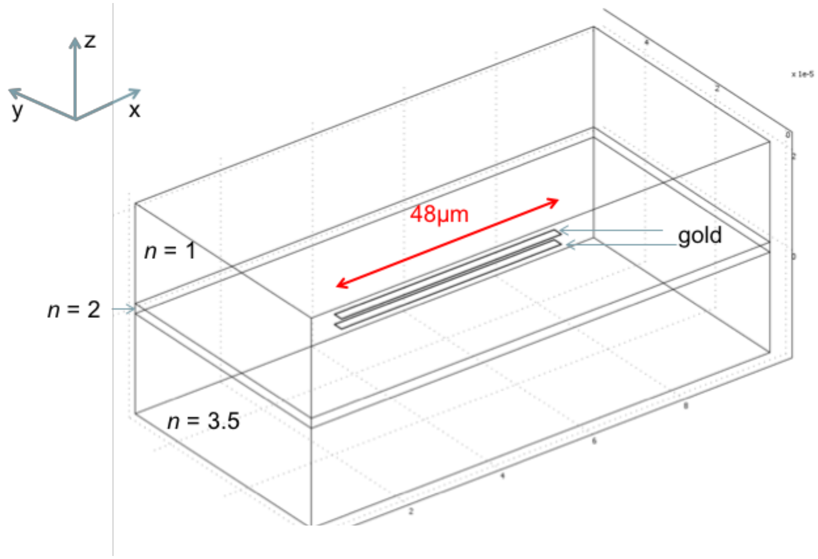
n_{eff} = 2.1

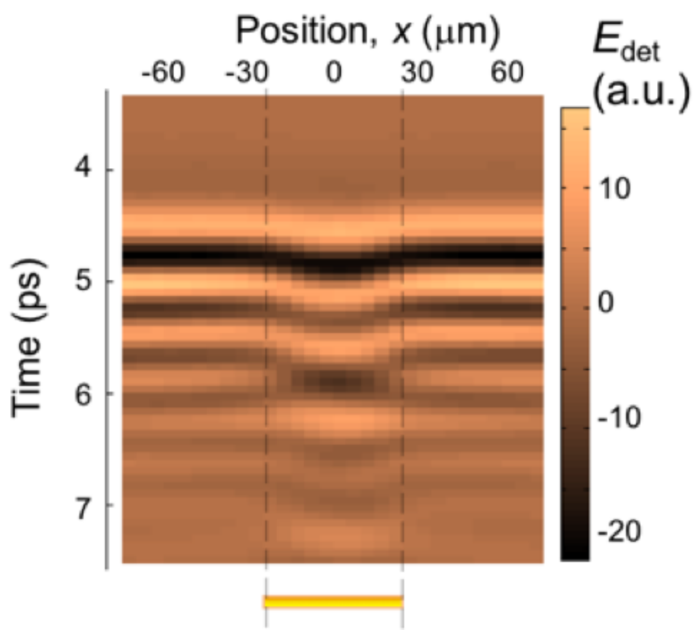
Field is in low index spacer

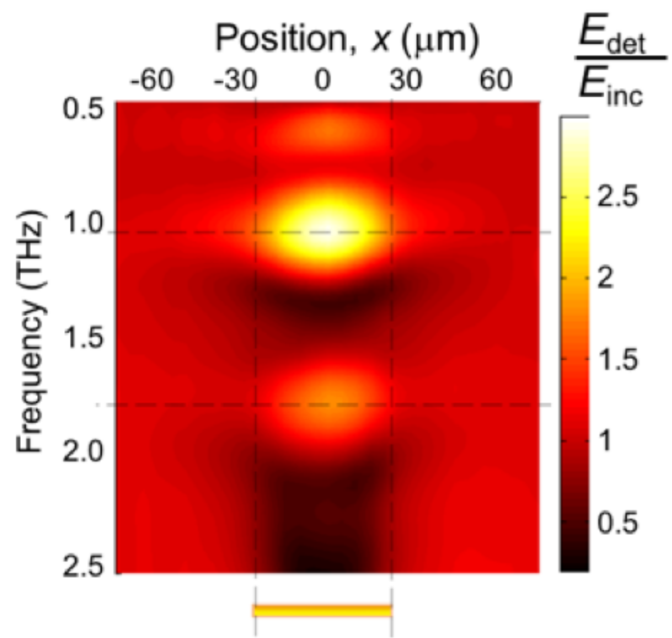




‘Double-metal’ antenna

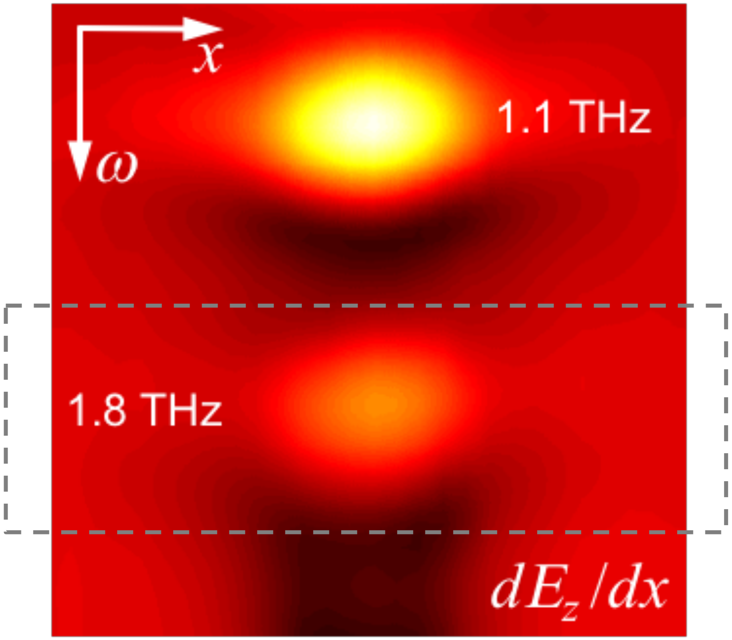


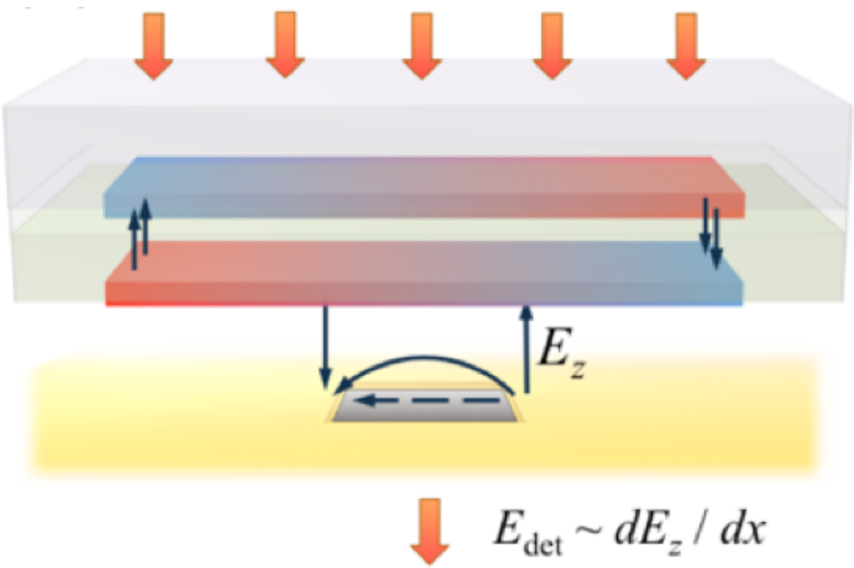




Mitrofanov, Todorov, et al., *Optics Express* (2018)

Detected fields

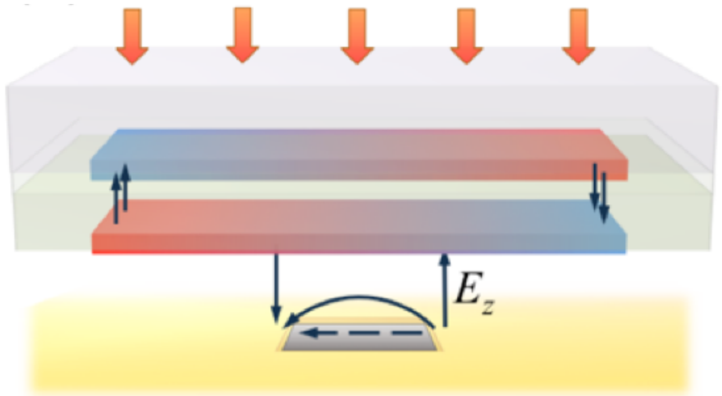


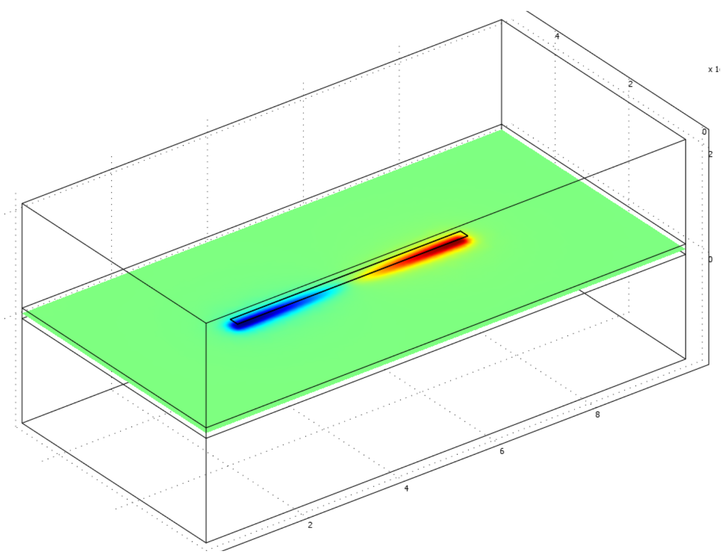


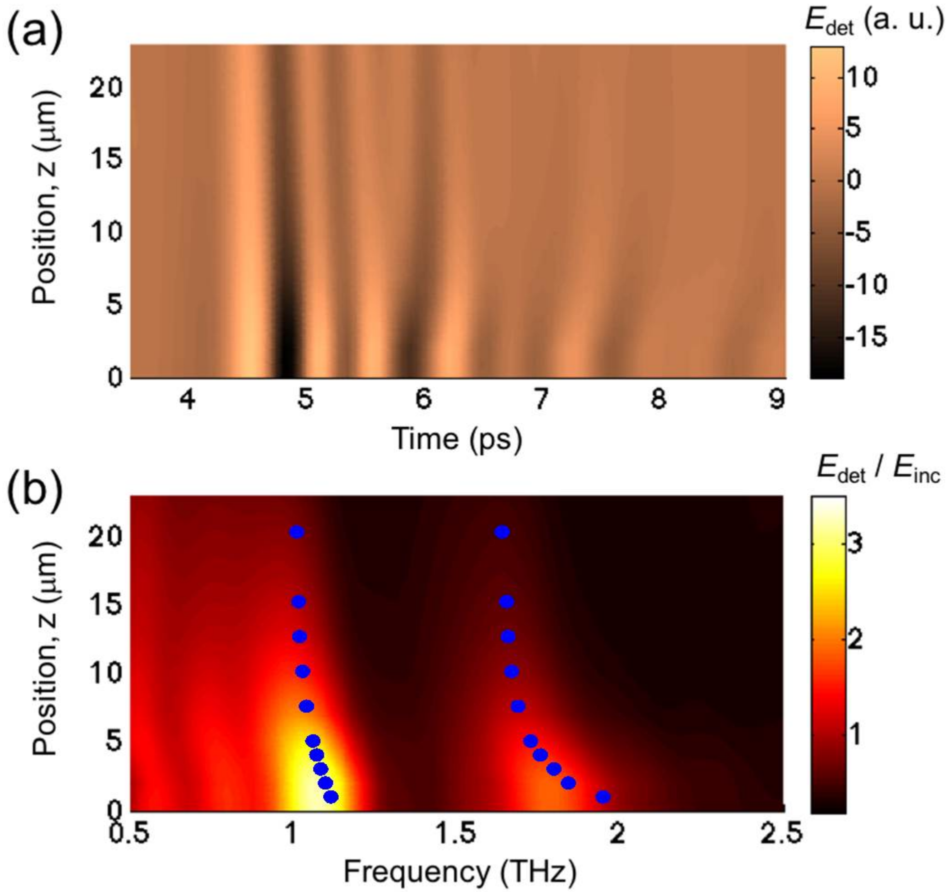
Mitrofanov, Todorov, et al., *Optics Express* (*in press*)

Near-field probe functionality

Sample-probe distance: *Frequency 'Tuning'*

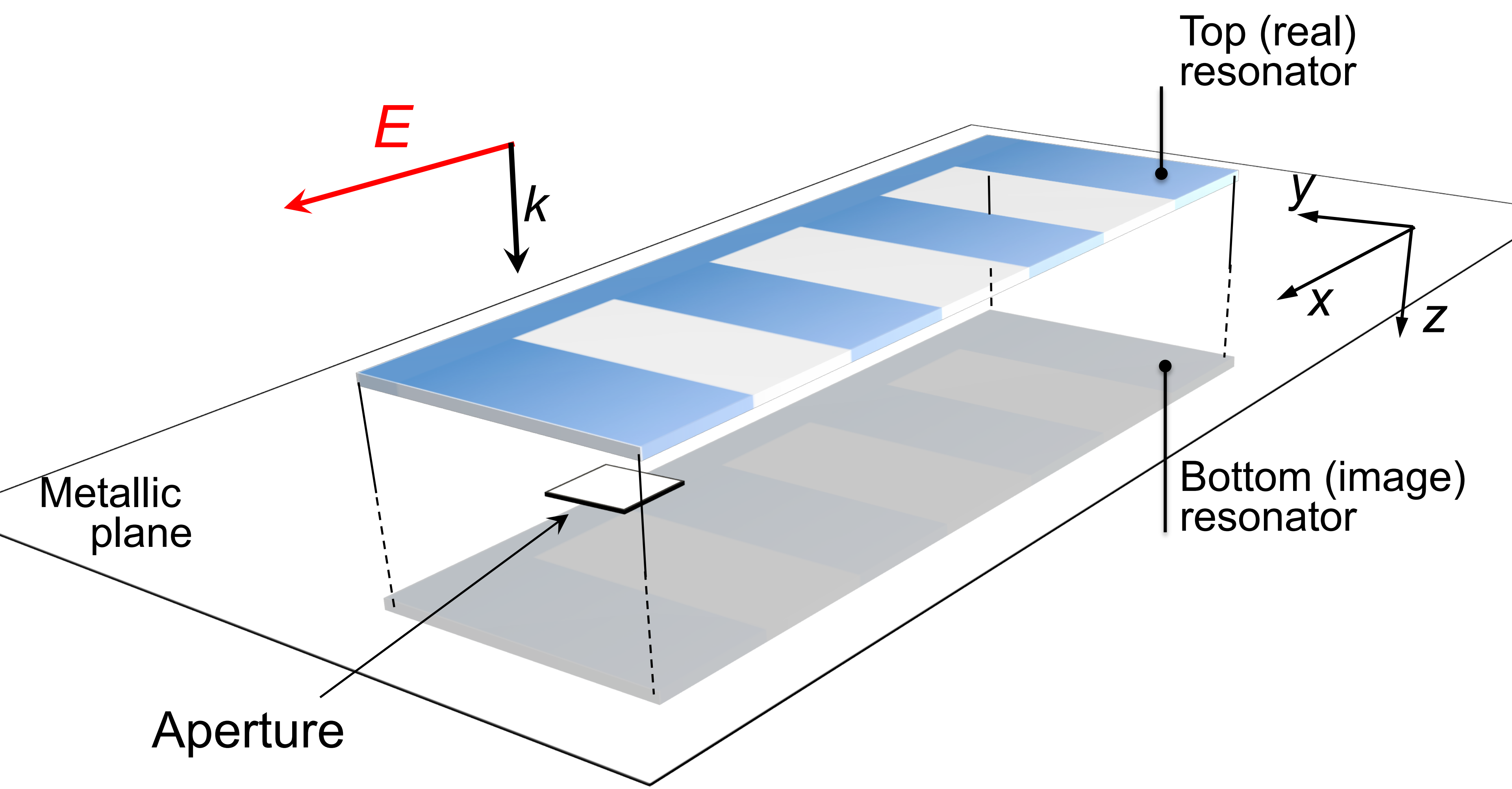






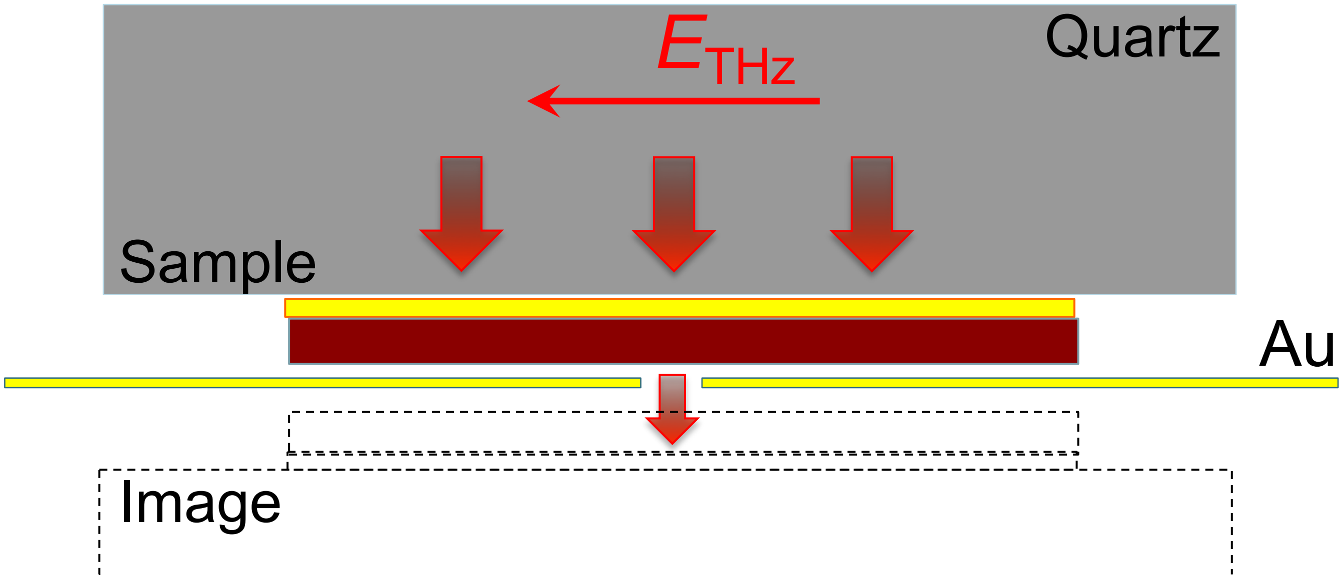
Mitrofanov, Todorov, et al., *Optics Express* (*2018*)

‘Double-metal’ resonator using image charges

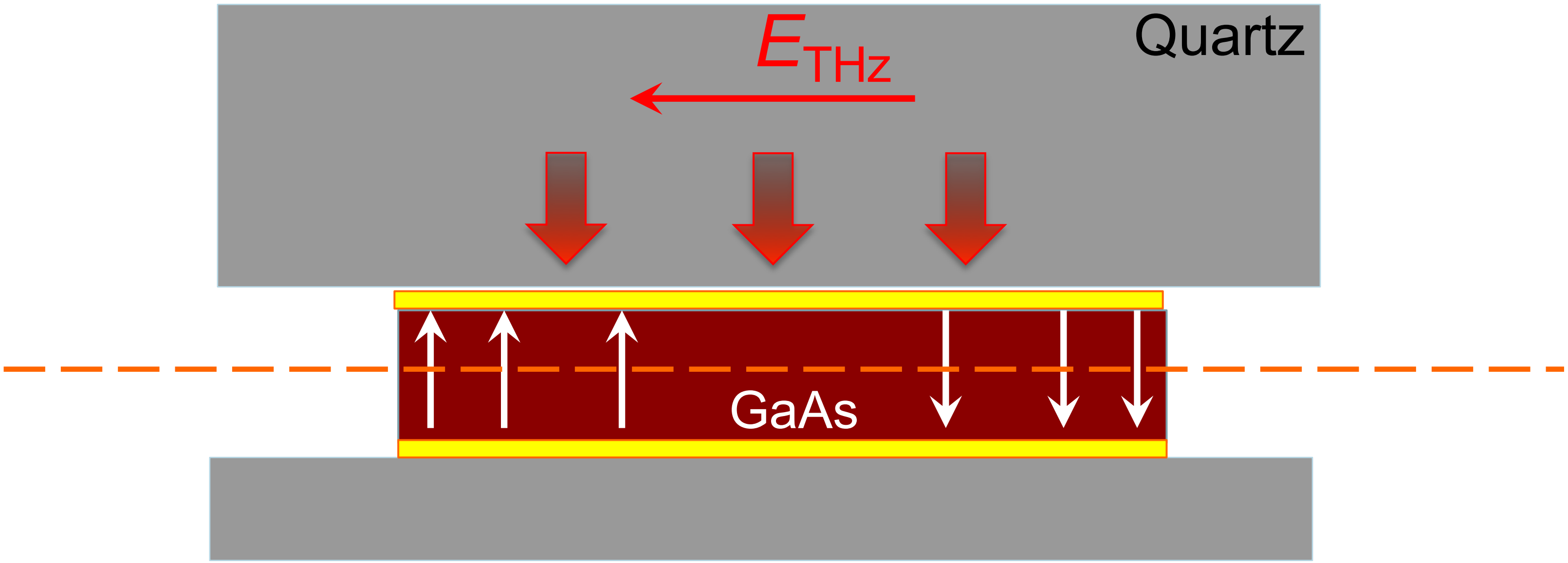


Mitrofanov et al., *Appl Phys Lett* (2017)

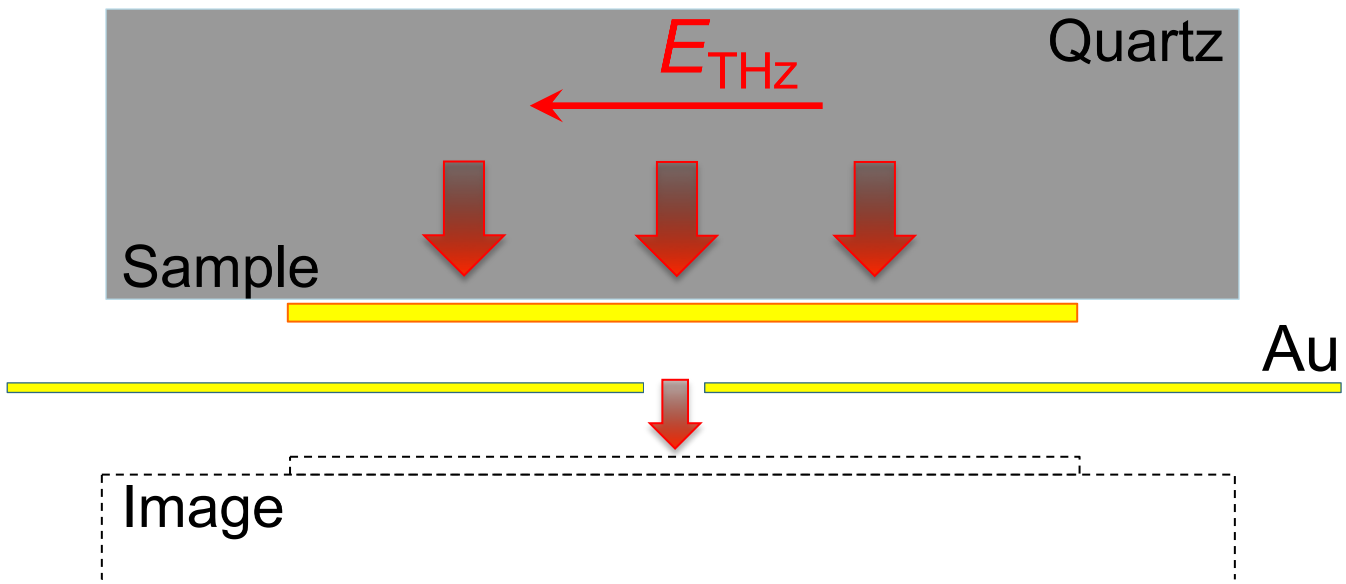
'Double-metal' resonator using image charges



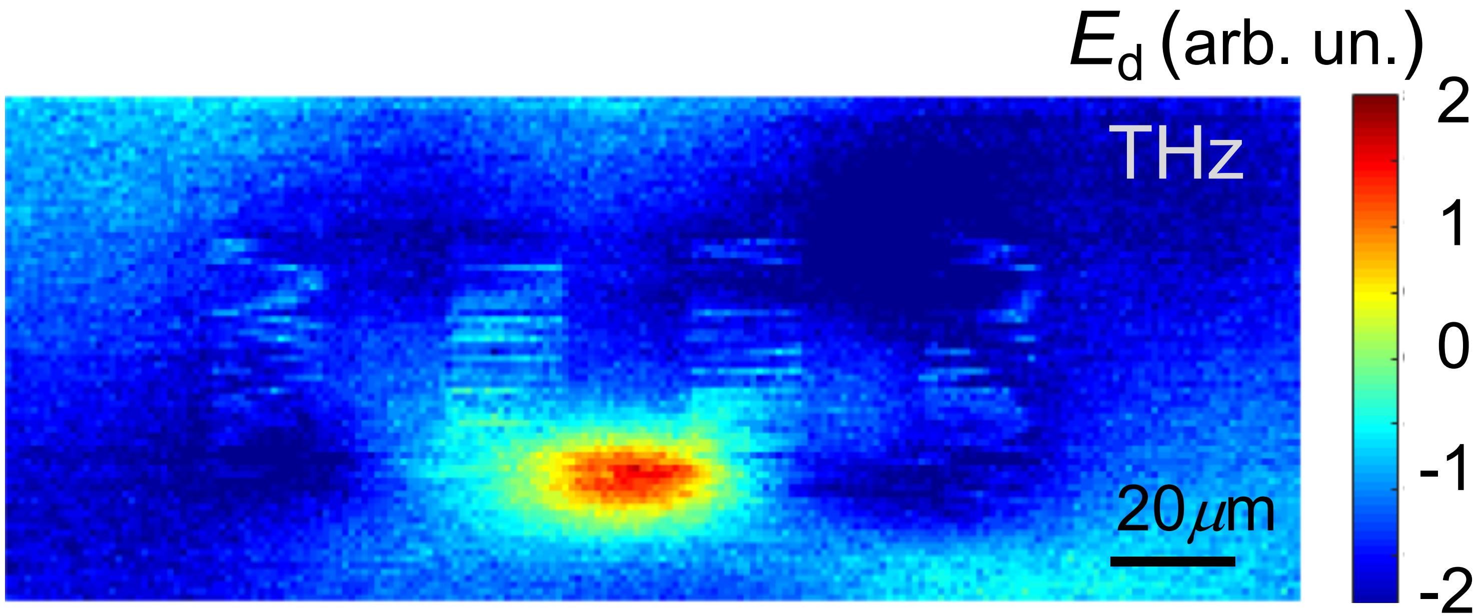
‘Double-metal’ resonator using image charges

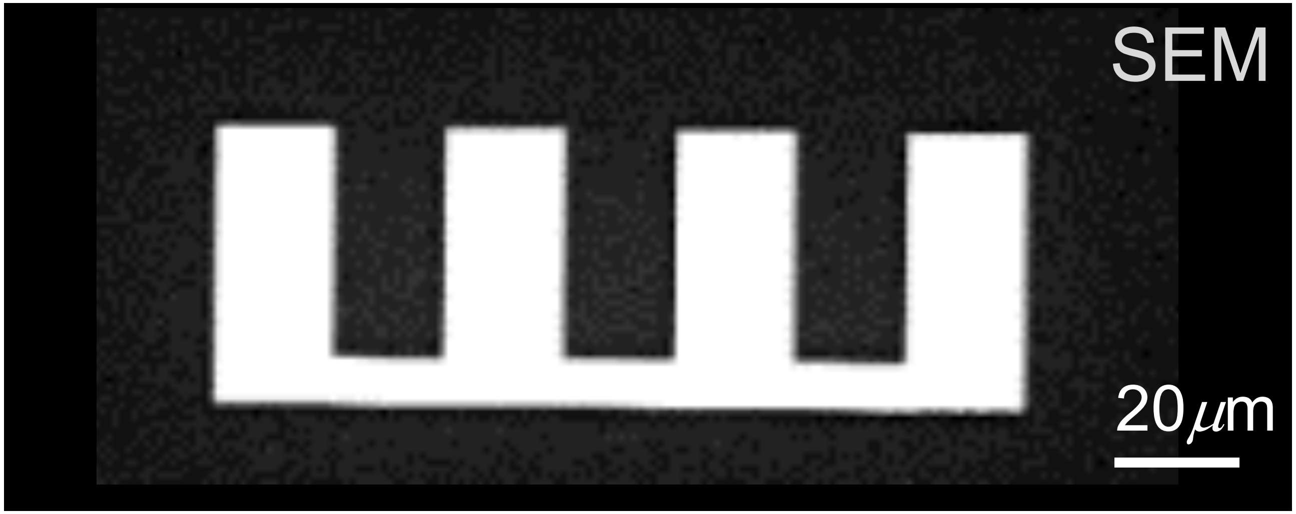


Air-filled double-metal resonator



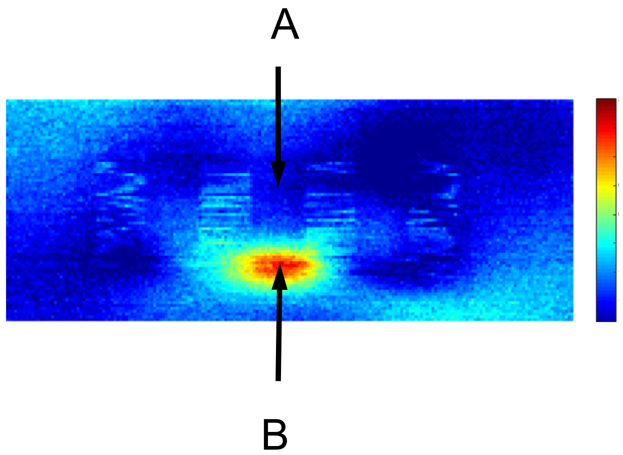
Experiment: near-field distribution

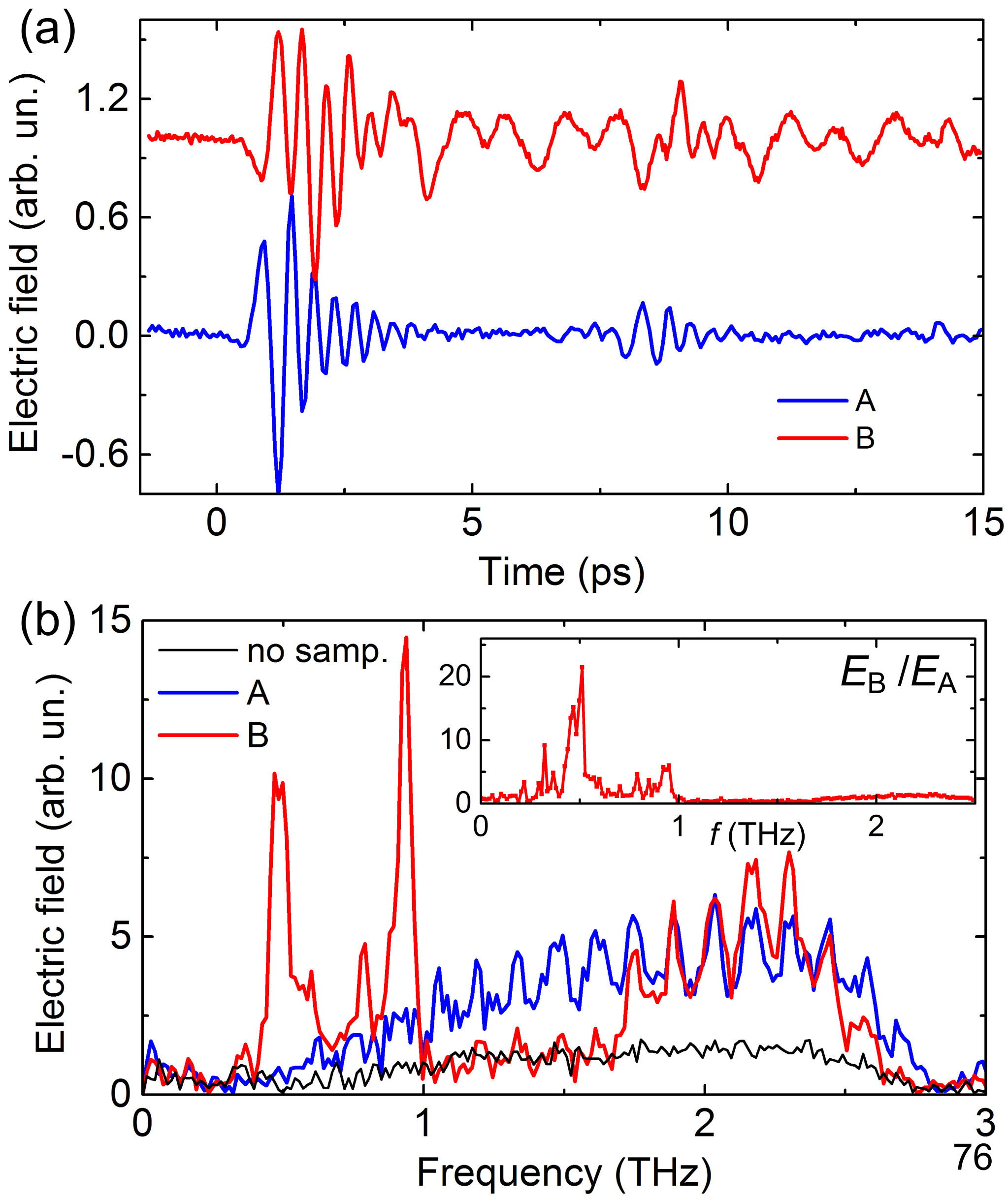




Mitrofanov et al., *Appl Phys Lett* (2017)

Near-field THz TD Spectroscopy





Spectral features:

1. Resonance at ~0.5 THz
(the enhancement is quite high ~20)

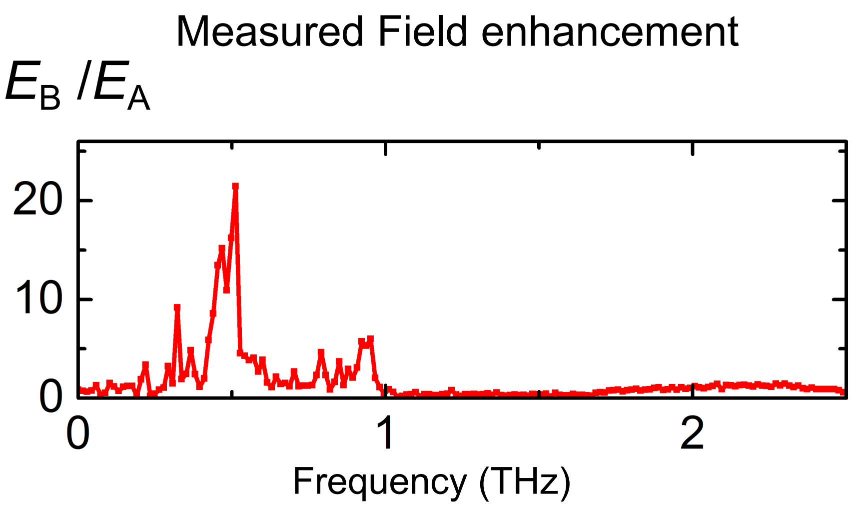
2. Resonance at ~1 THz
(the field enhancement ~5)

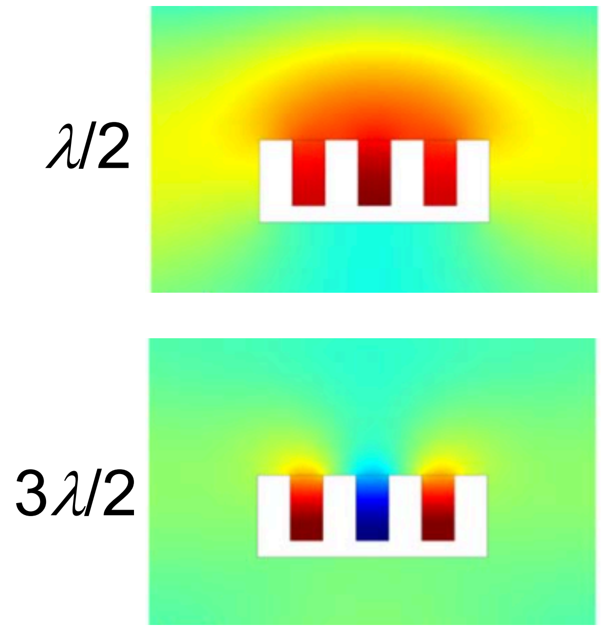
3. Field suppression 1-1.7 THz

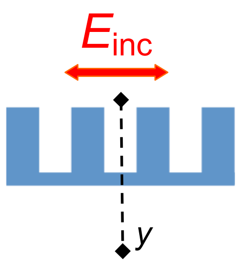
4. Broad band at > 2 THz

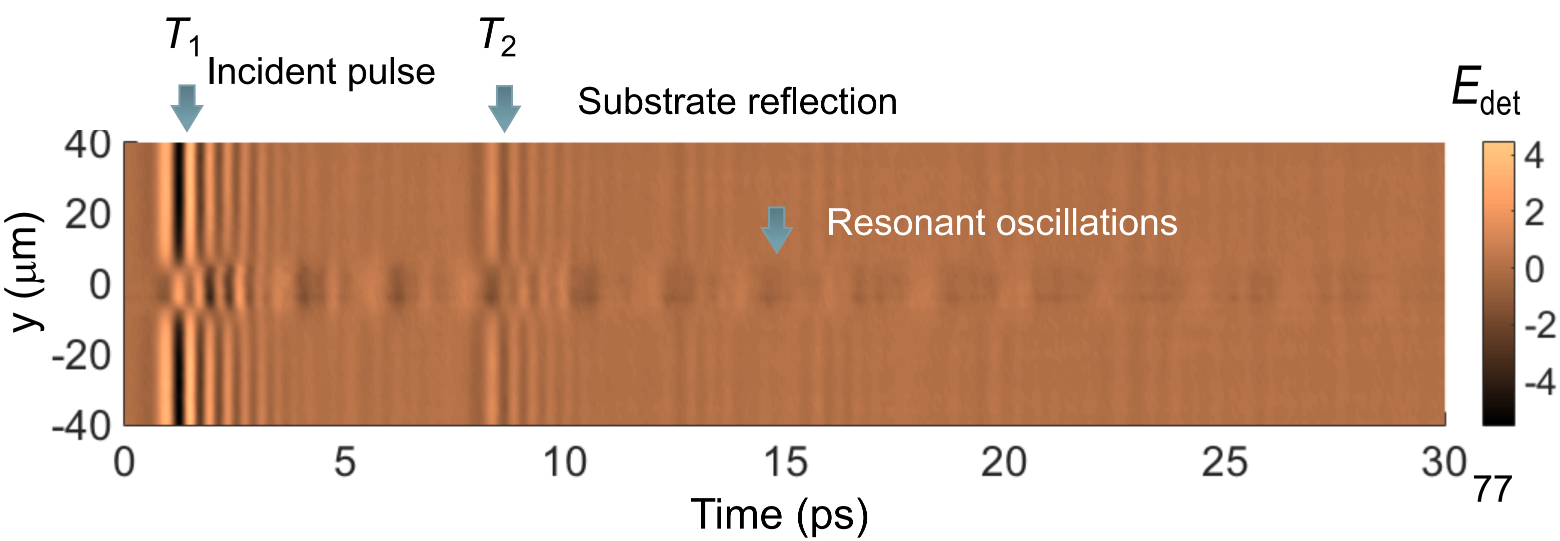
Mitrofanov et al., *Appl Phys Lett* (2017)

Mode identification

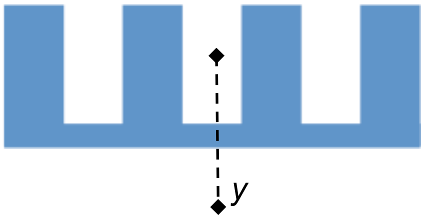


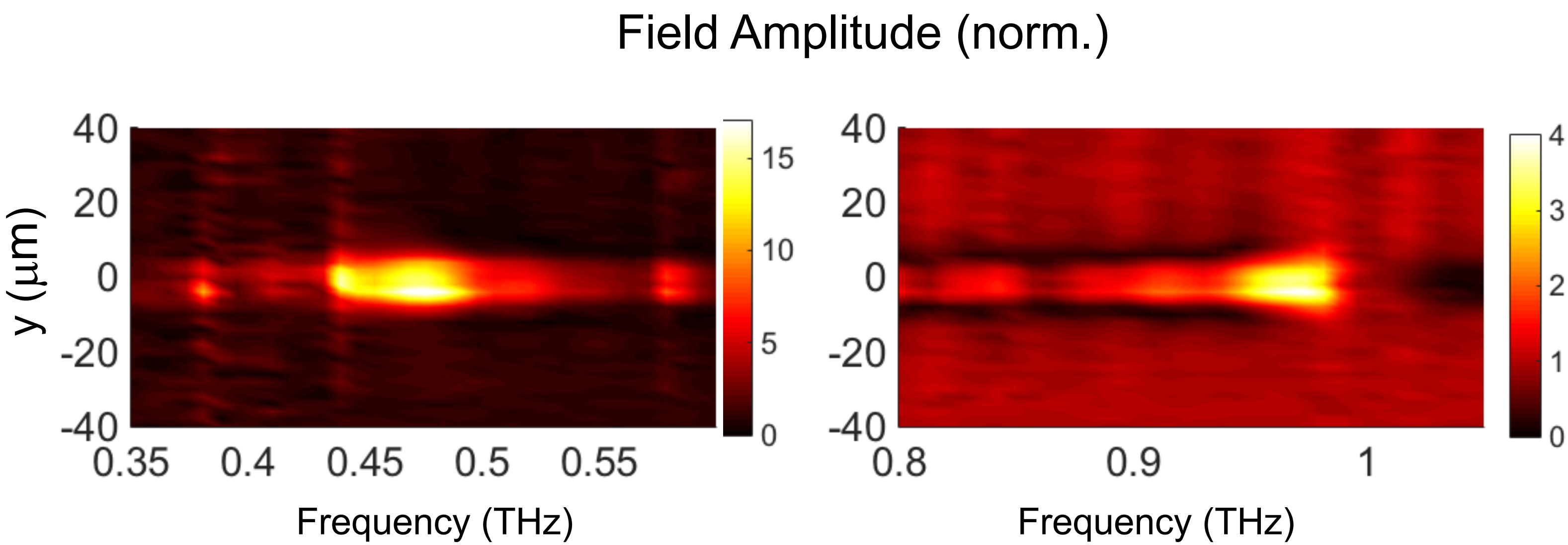






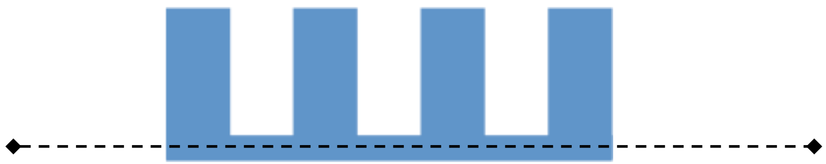
Mode identification – Field confinement

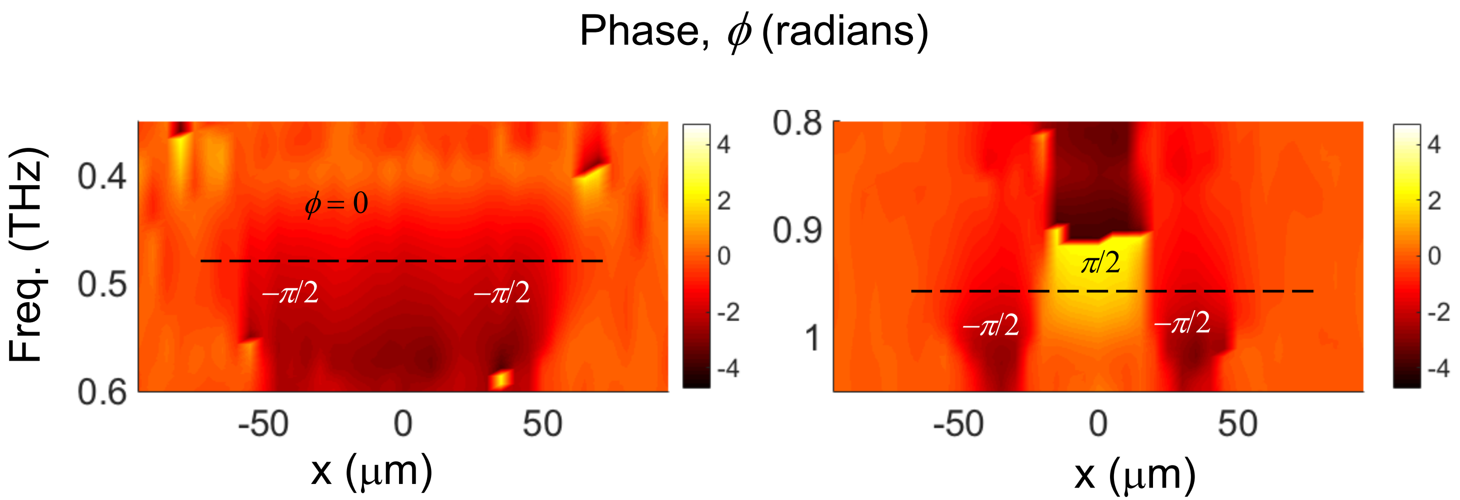


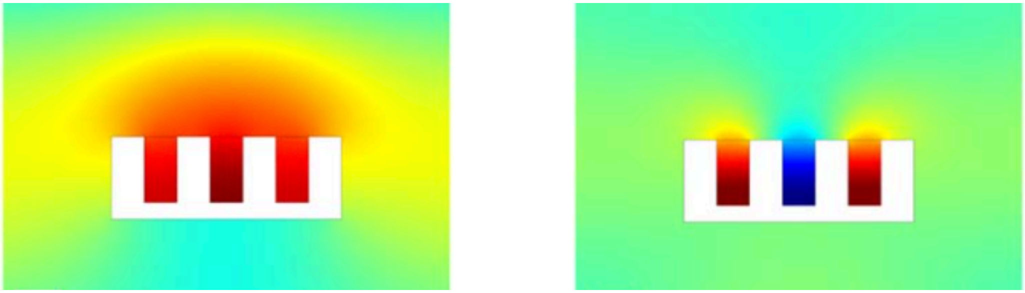


Mitrofanov et al., *Appl Phys Lett* (2017)

Mode identification - Phase

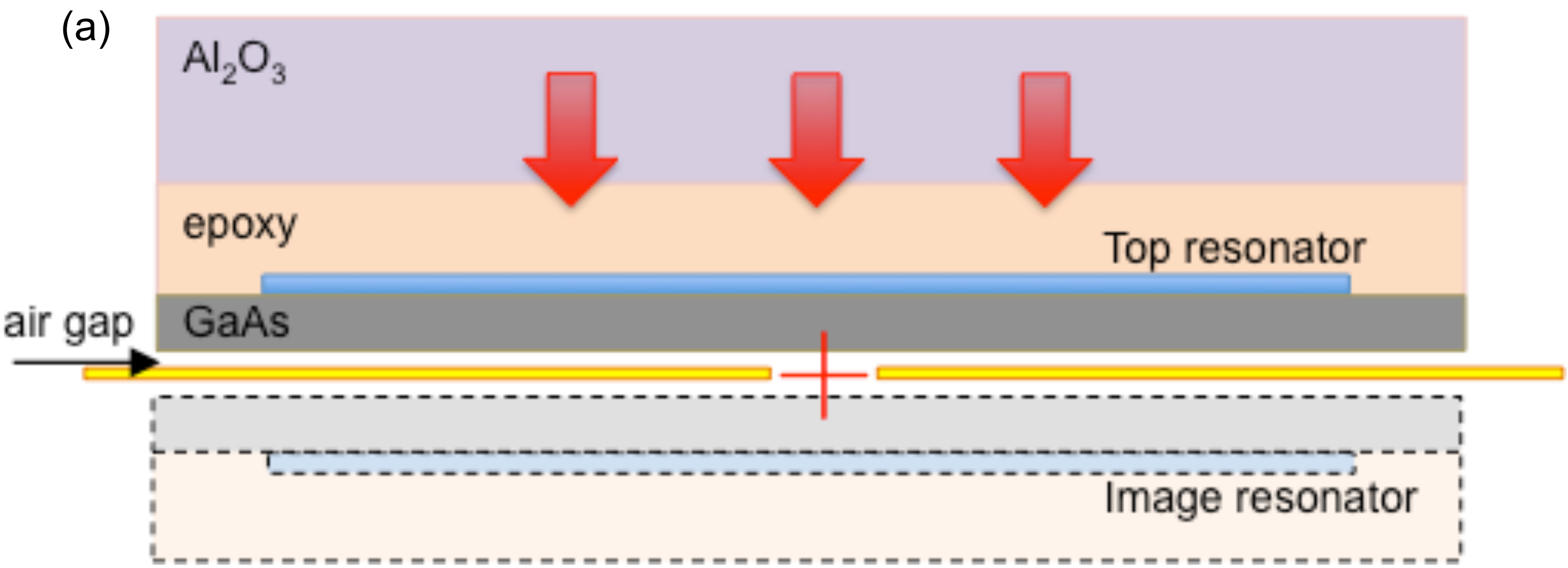




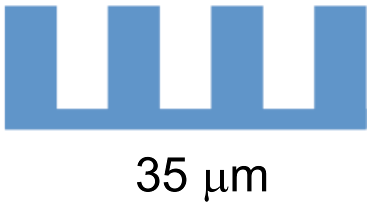


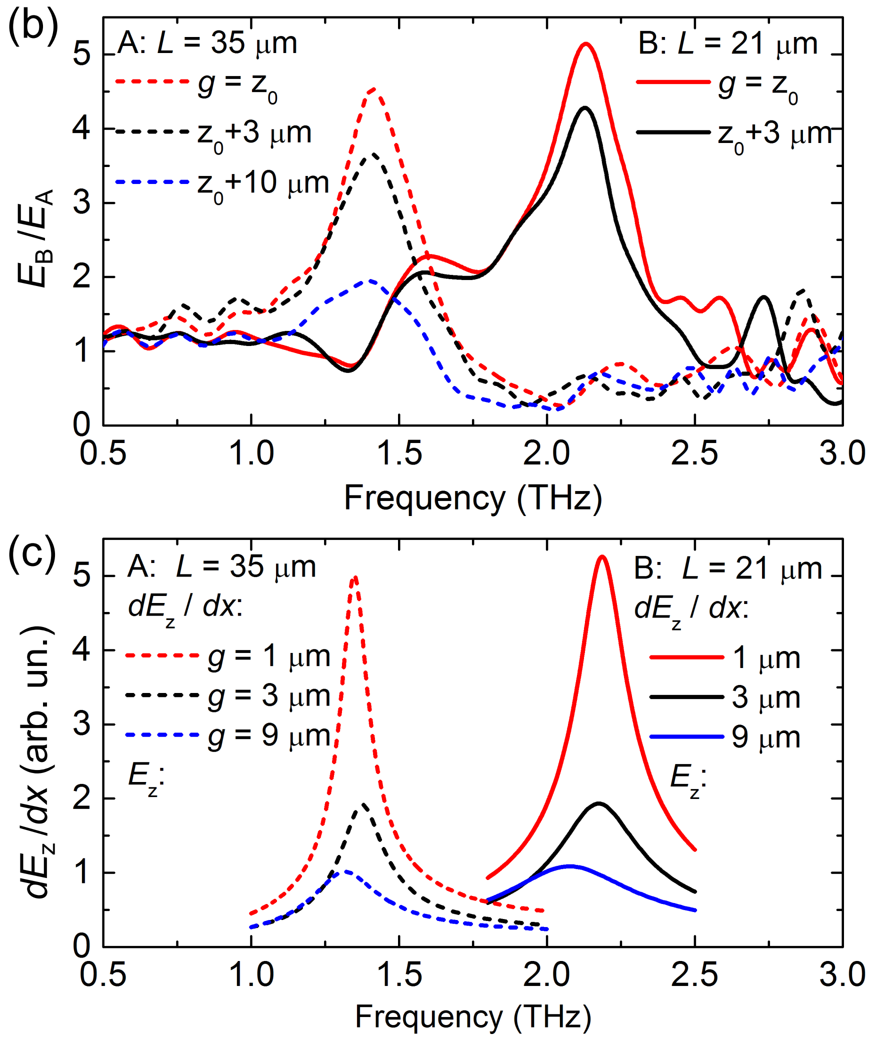
Mitrofanov et al., *Appl Phys Lett (2017)*

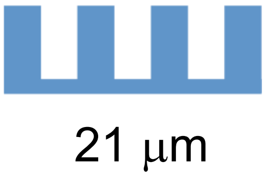
GaAs-filled THz resonators



Spectroscopy of GaAs-filled resonators





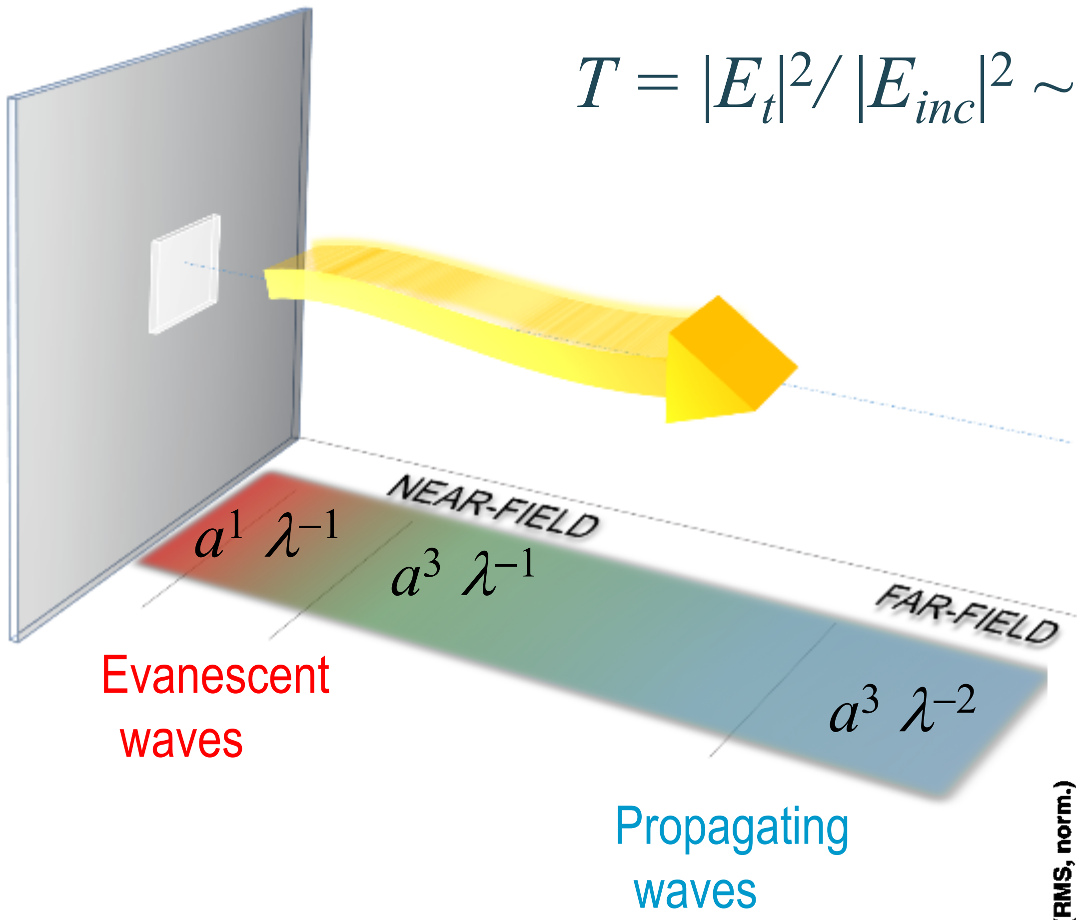


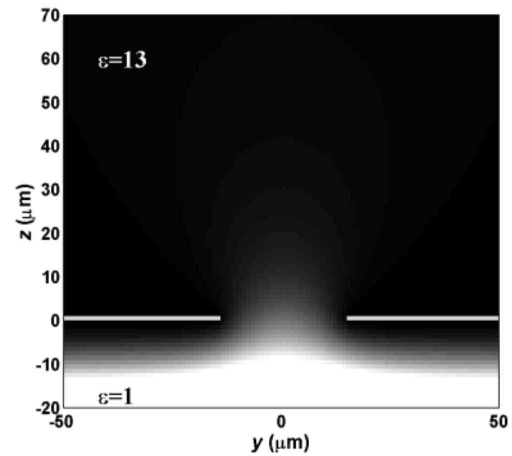
NF Probes with embedded detectors

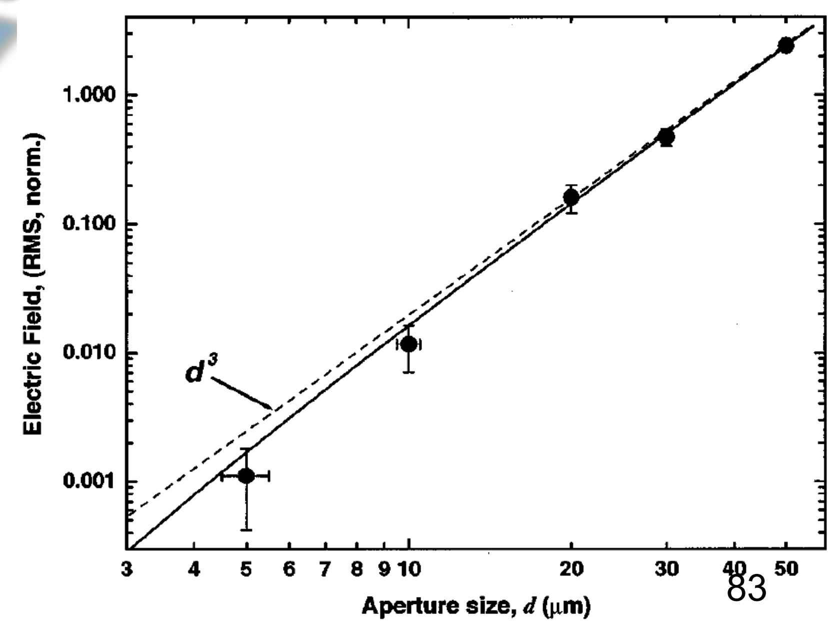
Spatial resolution and sensitivity

Wave transmission through subwavelength apertures

$$T = |E_t|^2 / |E_{inc}|^2 \sim a^6$$



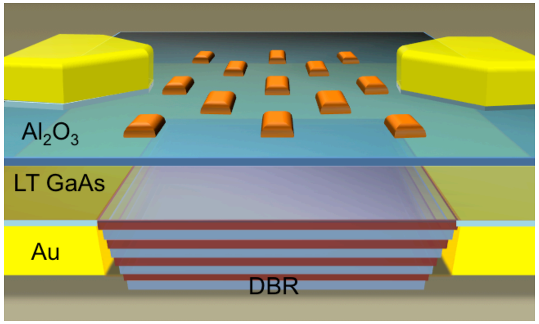


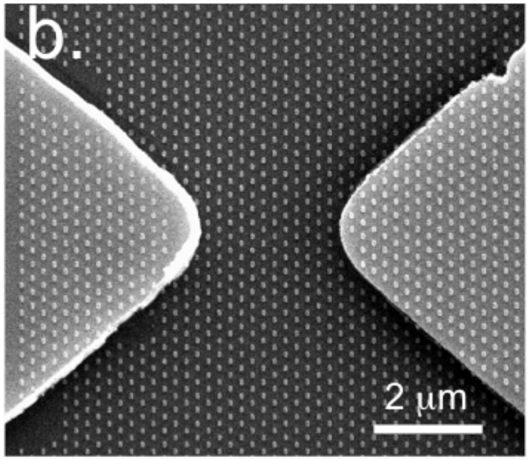


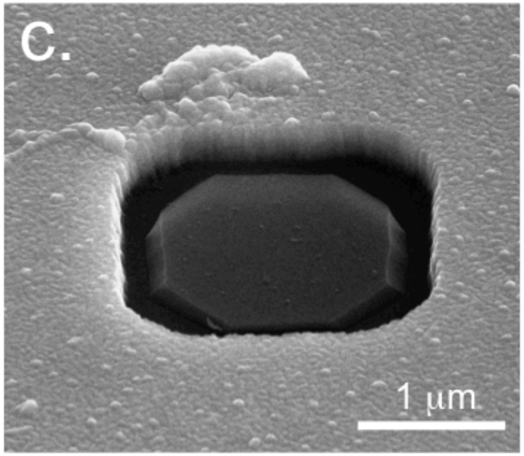
Mitrofanov et al., APL **77**, 3496 (2000)
APL 79, 907 (2001)

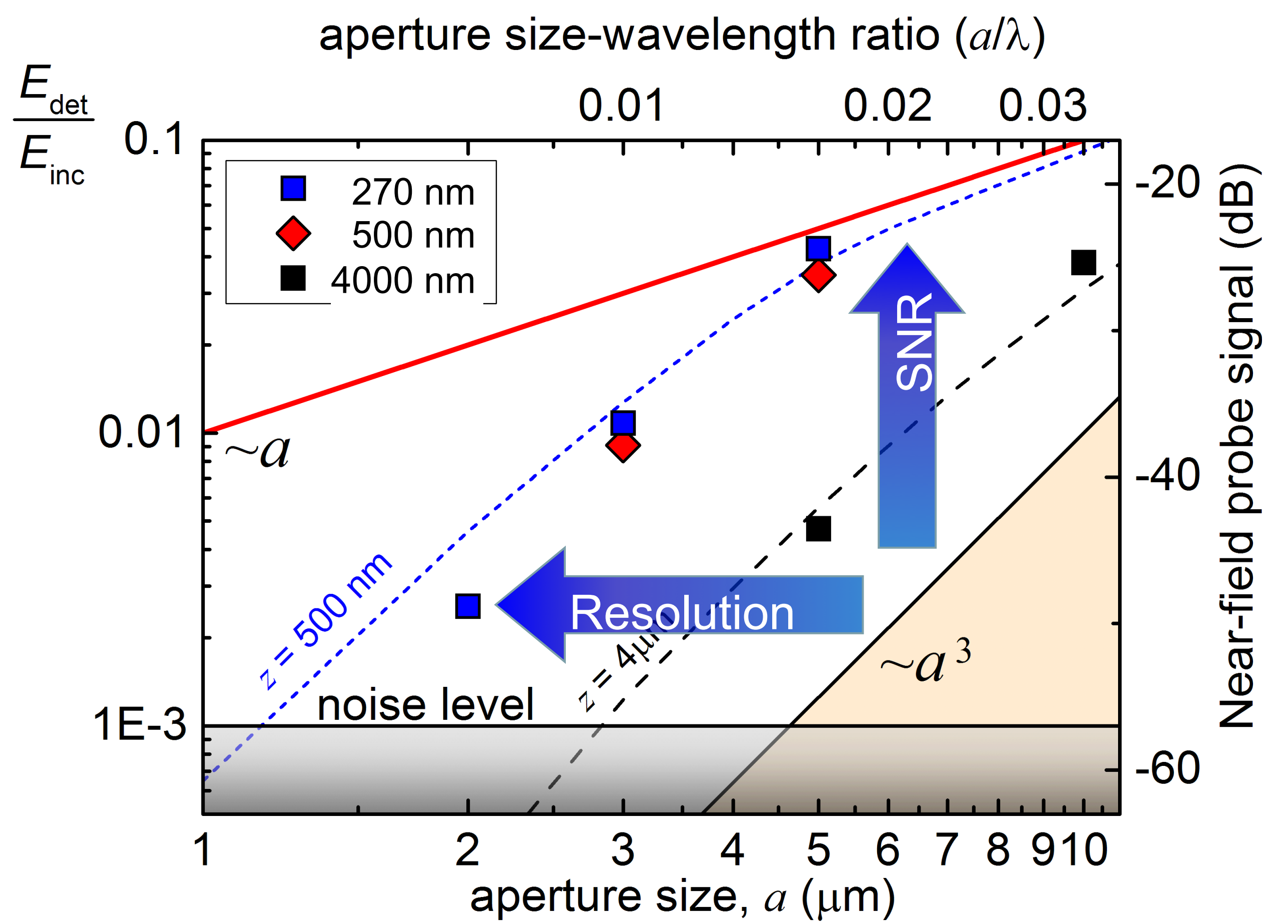
Adam, J IRMTW **32**, 976 (2011)

NF probe sensitivity





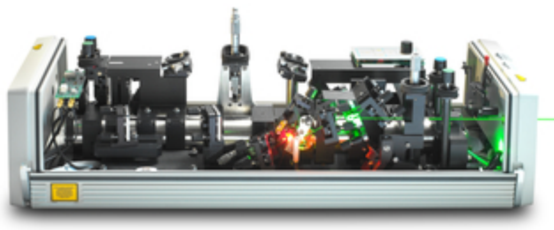




Mitrofanov et al.,
IEEE Trans. THz S&T (2016)

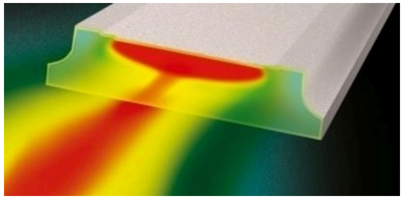
Mitrofanov et al.,
ACS Photonics (2015)

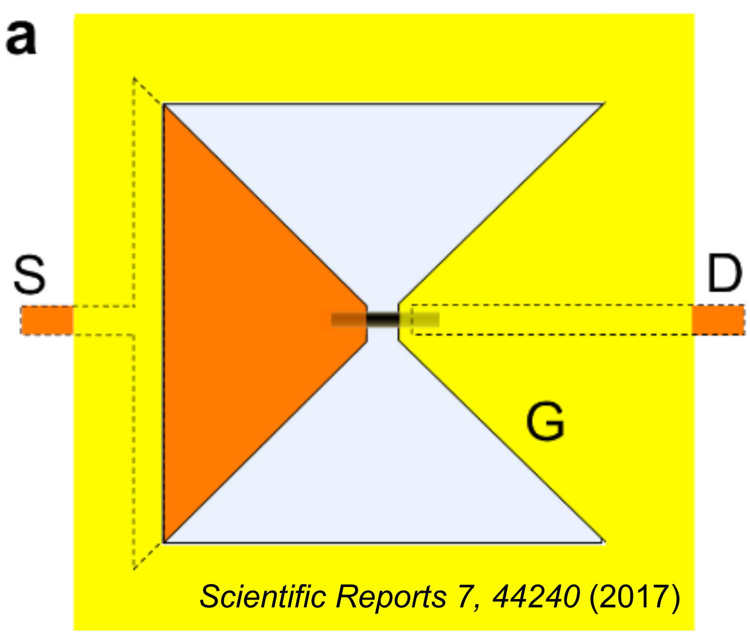
Integration of CW THz detector into aperture probe



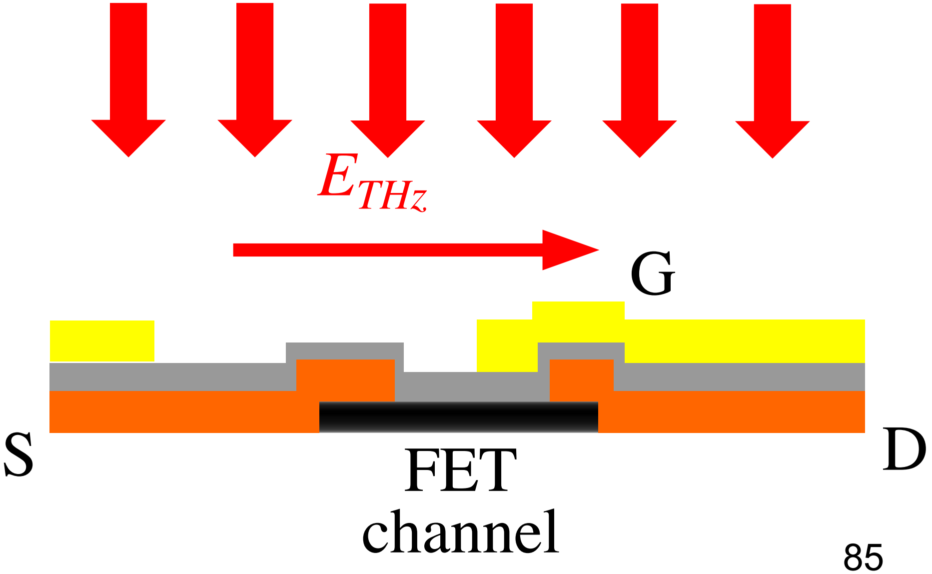
Femtosecond pulse laser
Spectra-Physics

THz Quantum Cascade Laser
CNR

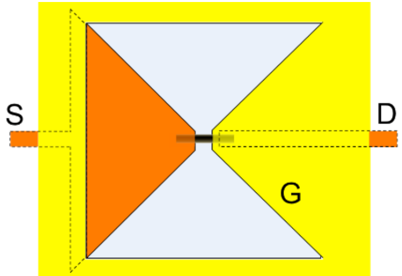


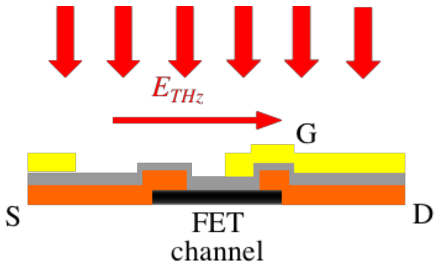


Scientific Reports 7, 44240 (2017)

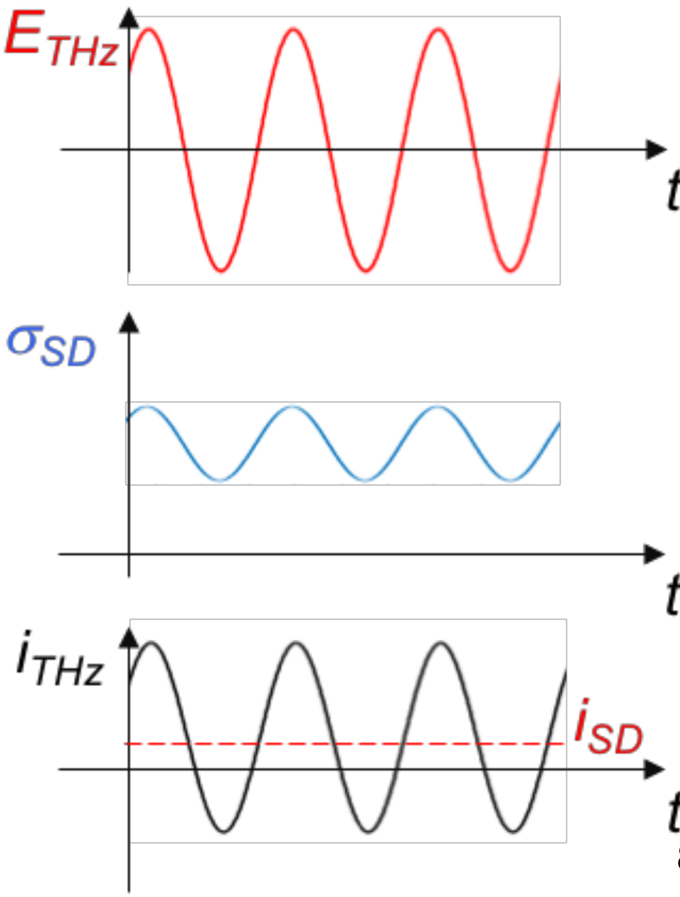


Detection





THz modulation
of charge carrier density



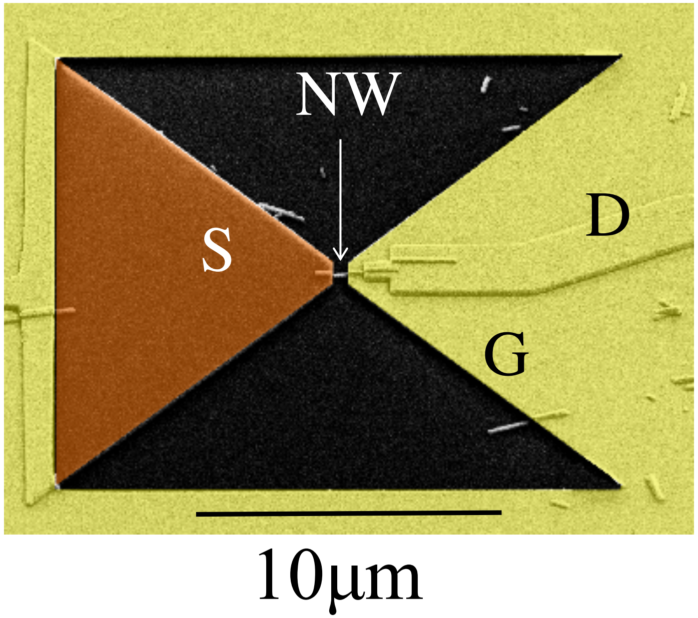
Asymmetric coupling of THz wave to the channel leads to a DC current or voltage across the channel

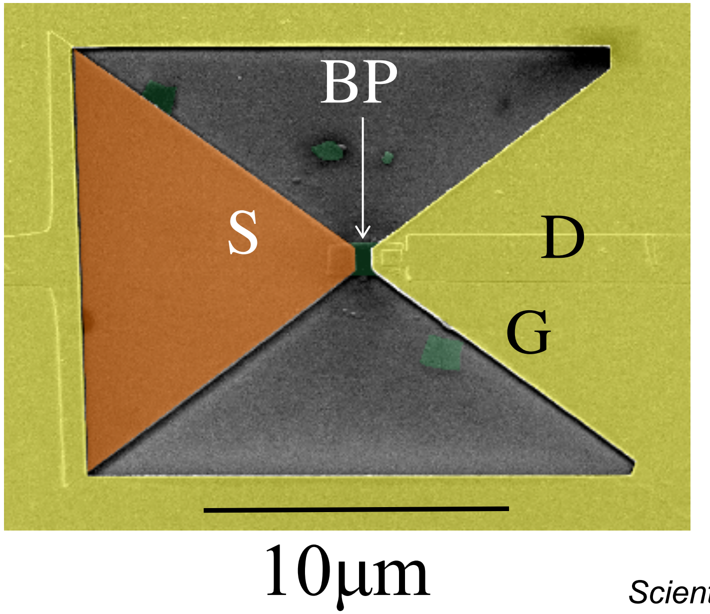
Detection mechanisms:

FET Rectification effect

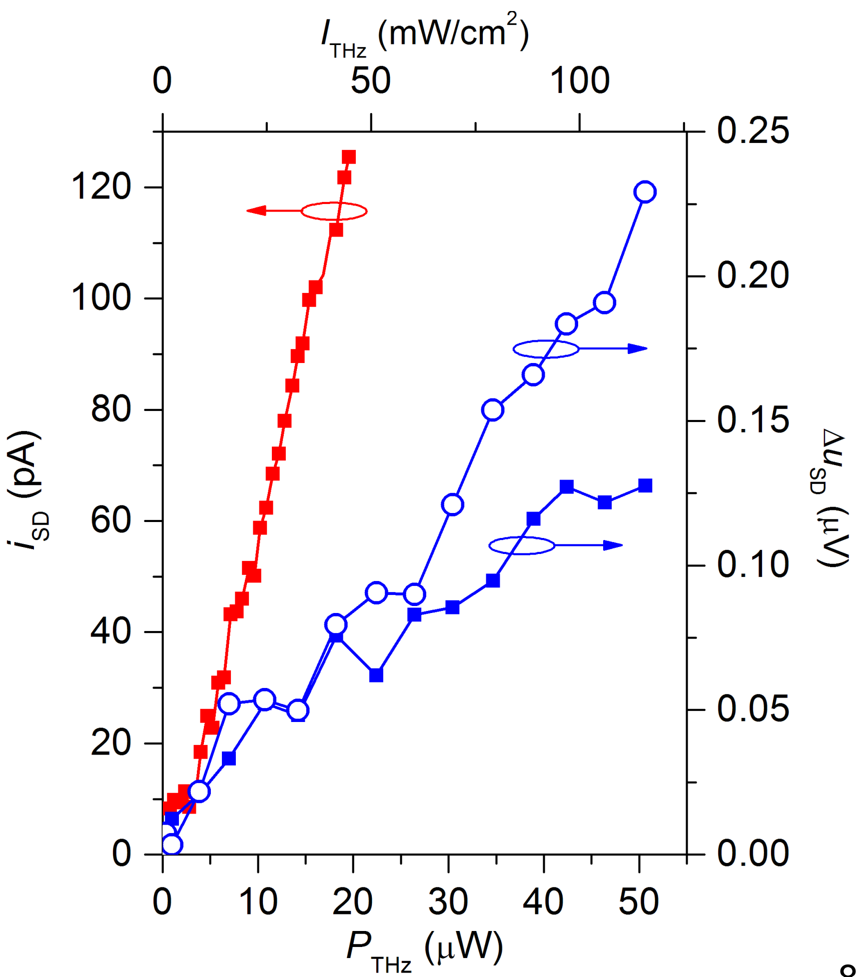
Thermoelectric effect

Detection



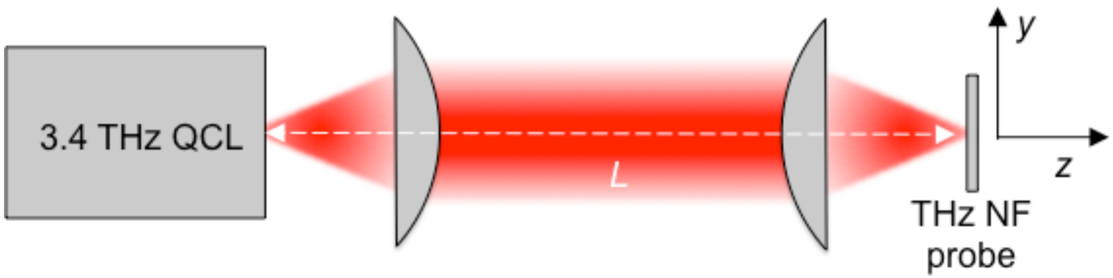


InAs nanowires and Black Phosphorus flakes operate as integrated FET THz detectors in PV and rectified current modes

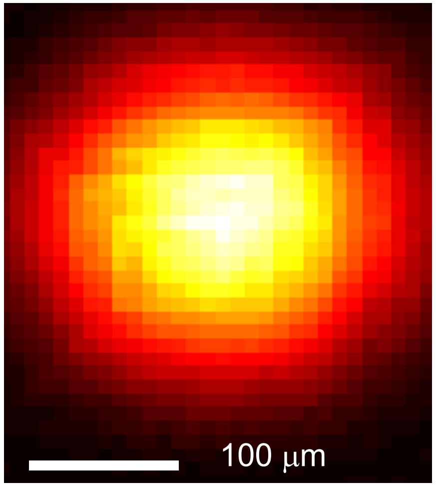


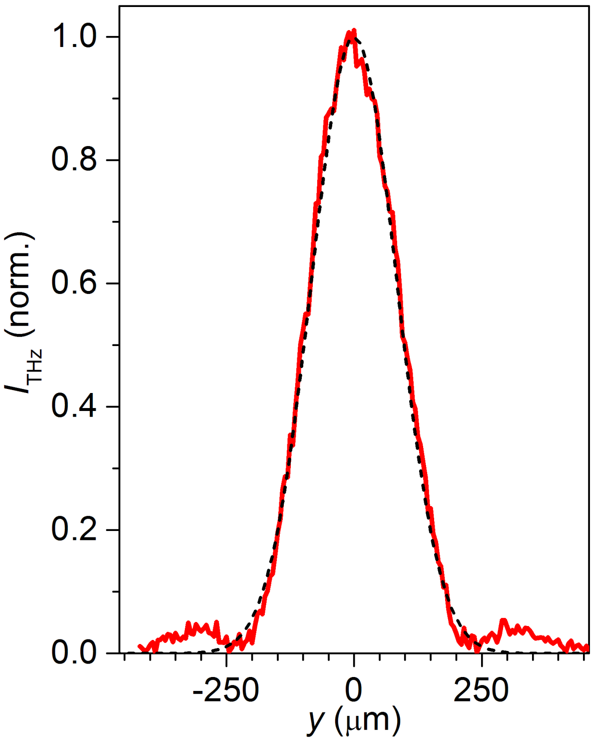
Scientific Reports 7, 44240 (2017)

QCL beam profile characterisation



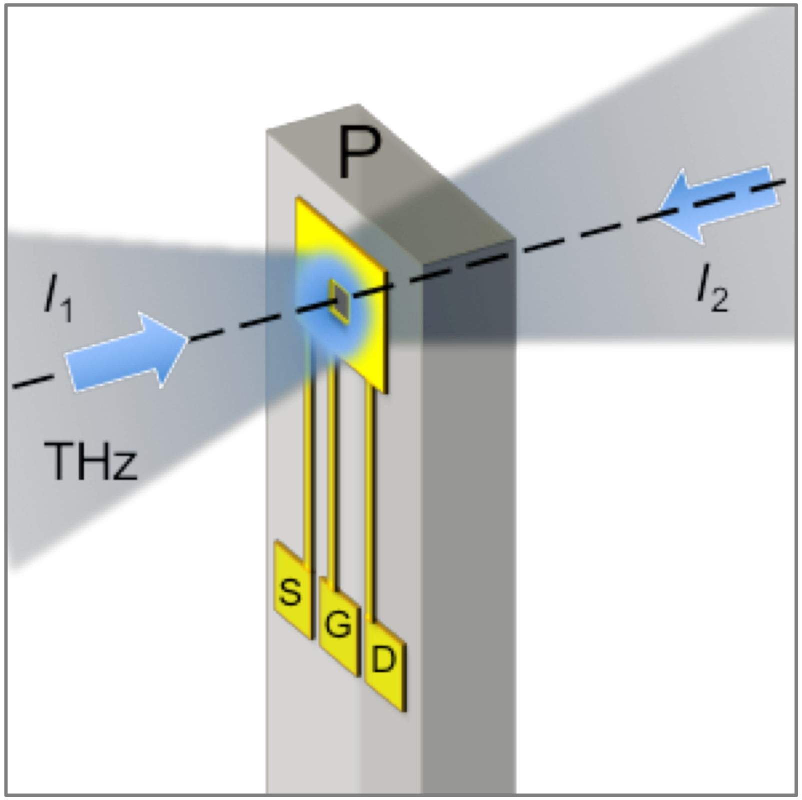
Beam profile in the focal plane

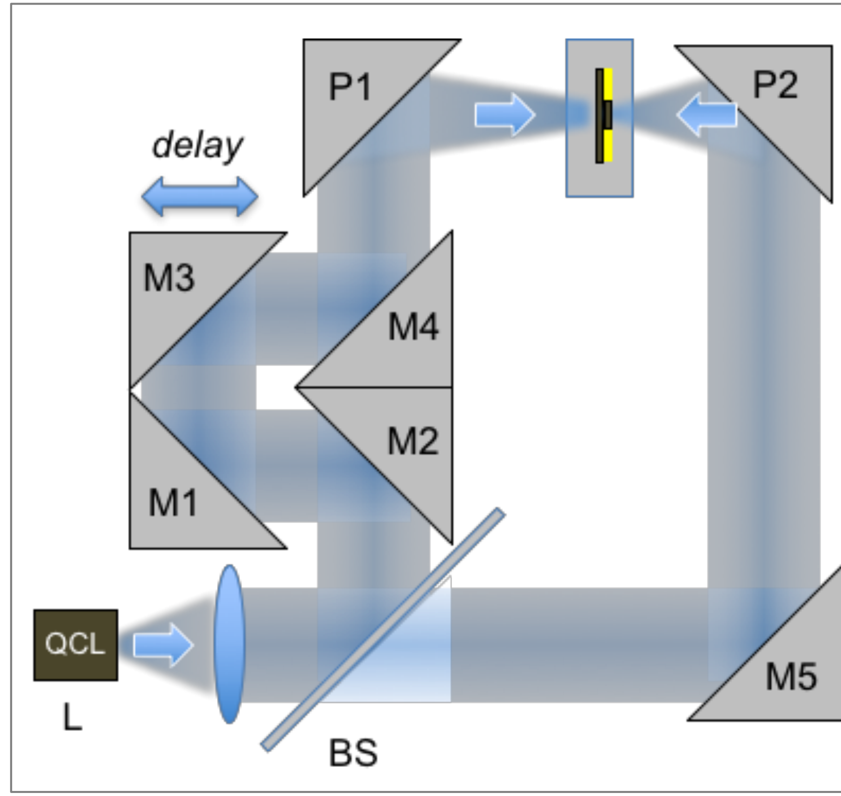




Scientific Reports 7, 44240 (2017)

Phase sensitivity – Local Interferometric Detection

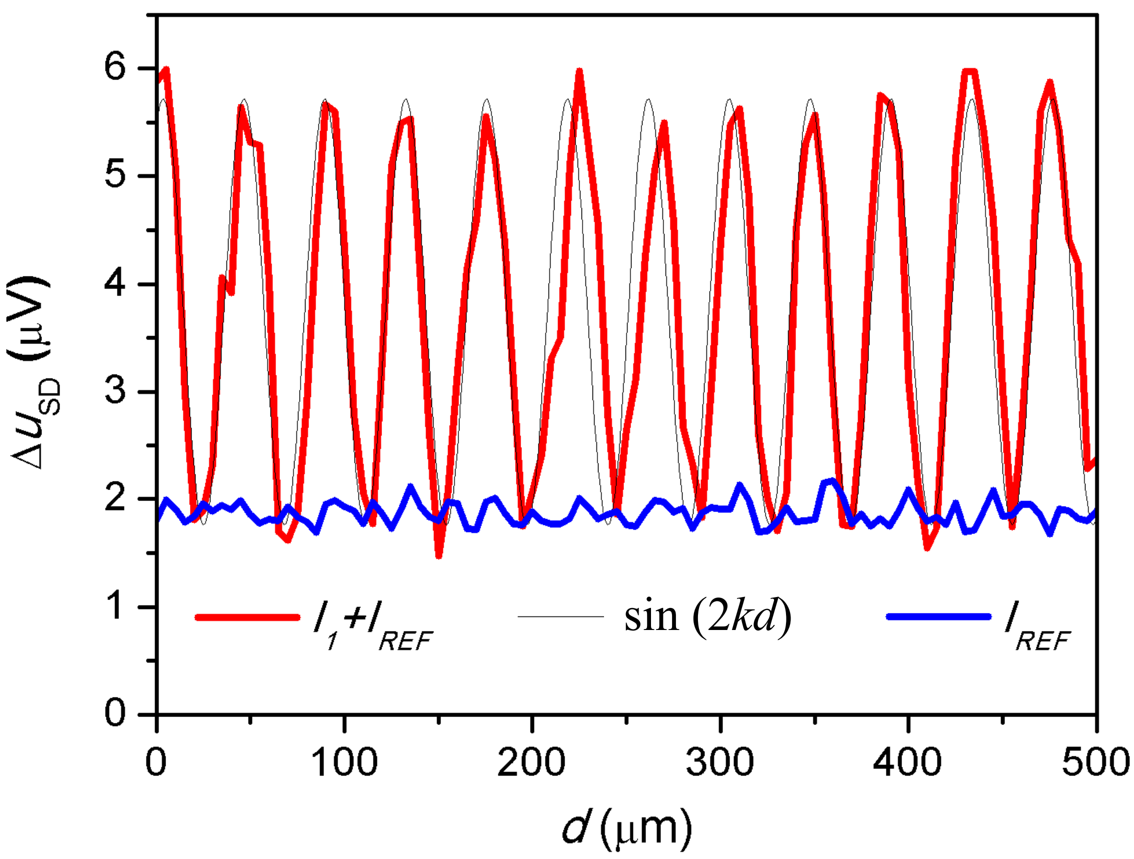


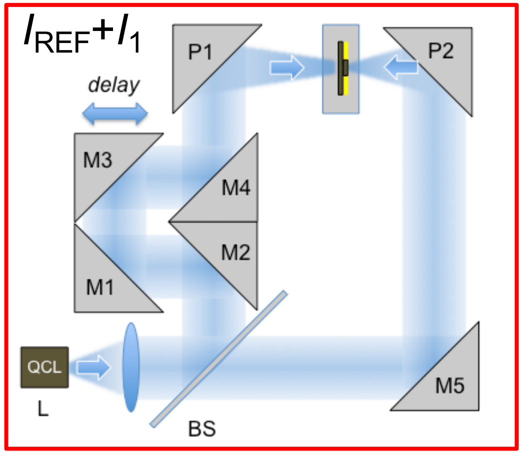


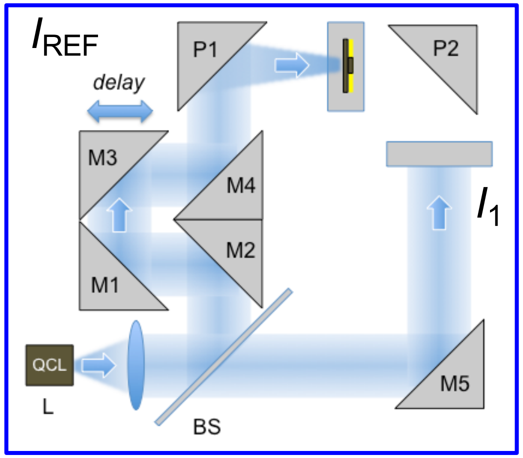
QCL: 3.4 THz, ~50 μW

Optica 5, 651-657 (2018)

Interference inside the probe



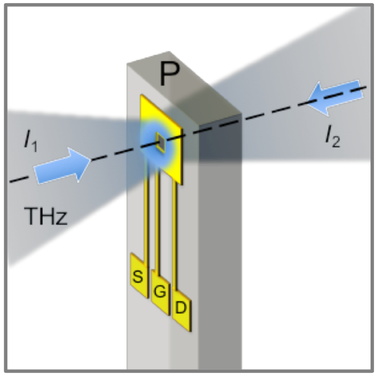


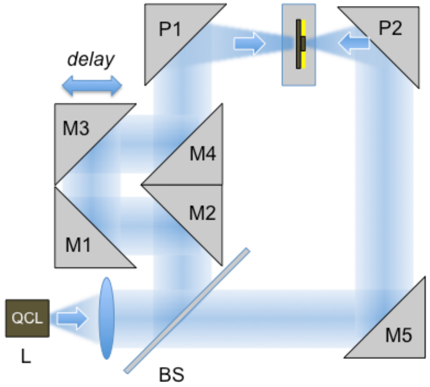


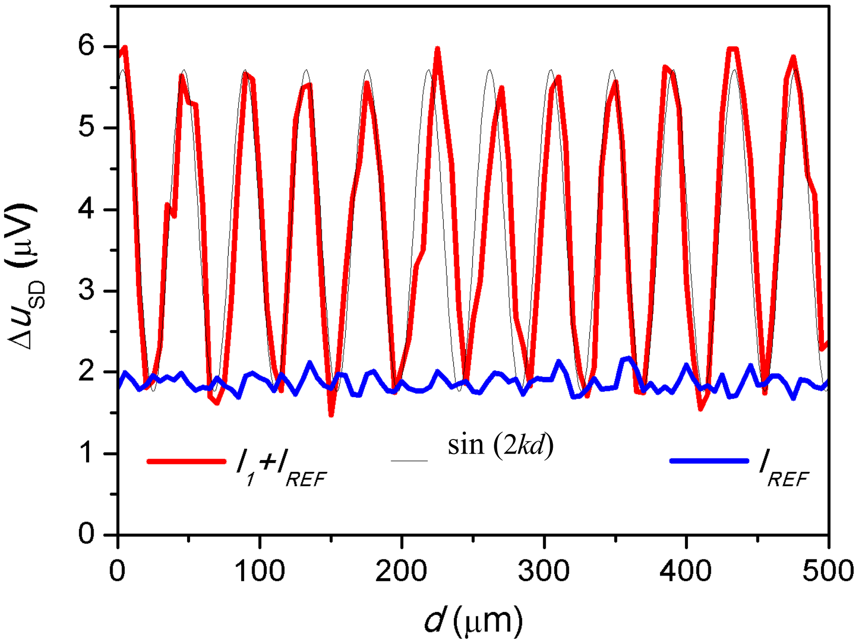
The detected signal depends on the phase

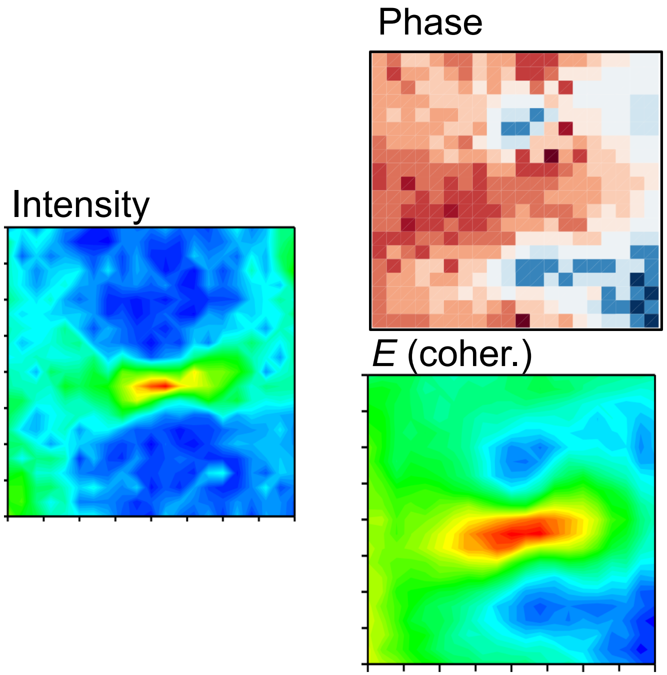
Coherent gain is observed: $(E_1 + E_{REF})^2 > E_1^2 + E_{REF}^2$

Interference inside the probe









Scientific Reports 7, 44240 (2017)

Optica 5, 651-657 (2018)

Summary and Conclusions

1. *Near-field light-matter interactions are rich in physics*

   and observation provide invaluable insight.

2. *There are several near-field techniques available*

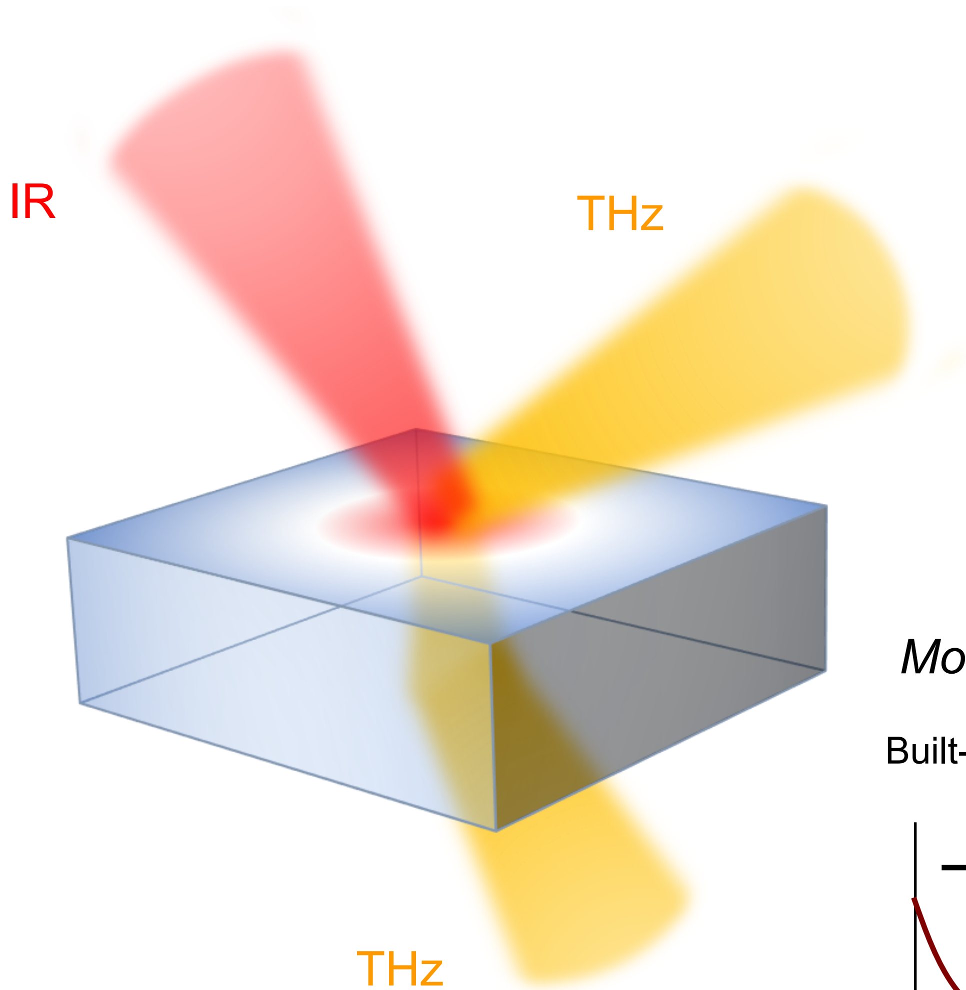
   it is ideal to develop a technique with the application in mind

3. *Resonators can produce THz magnetic fields*

4. *Surfaces waves / surface plasmon resonances can be probed by the aperture type THz microscopy*

Extra: NF Imaging Application - THz pulse generation

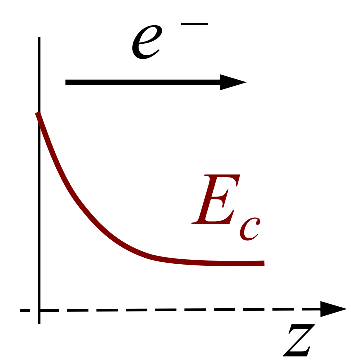
Transient current mapping



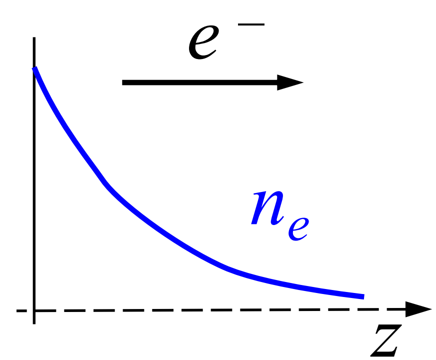
$$E \propto \frac{\partial I}{\partial t}$$

Models:

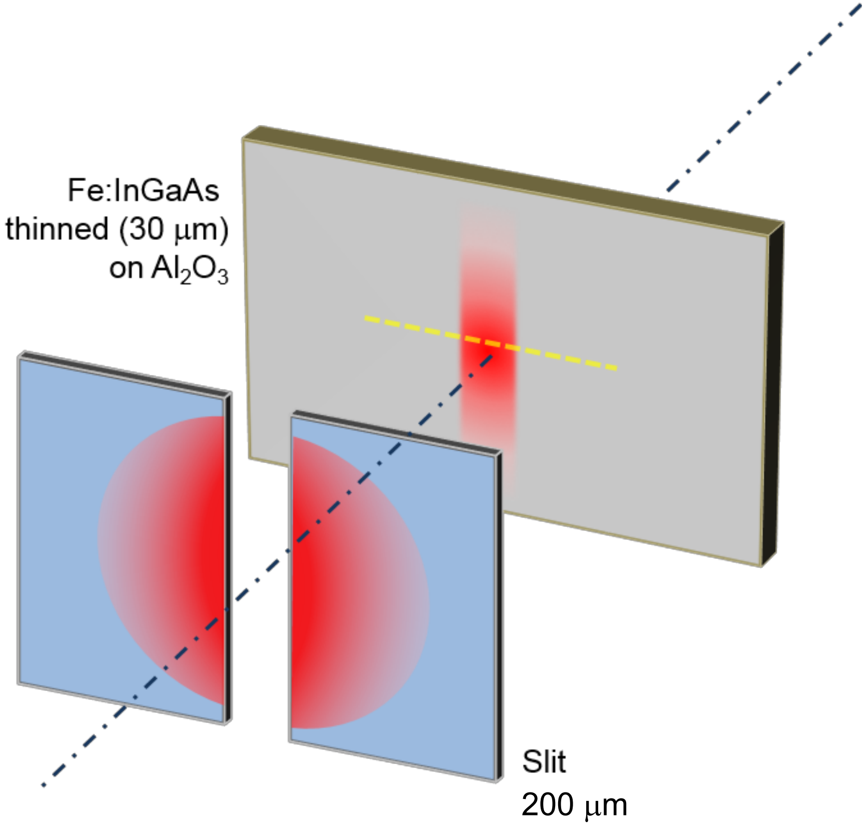
Built-in surface field

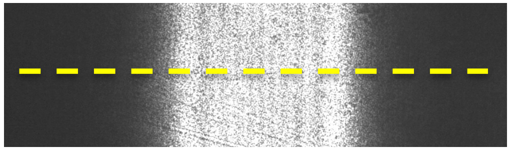


Carrier density gradient



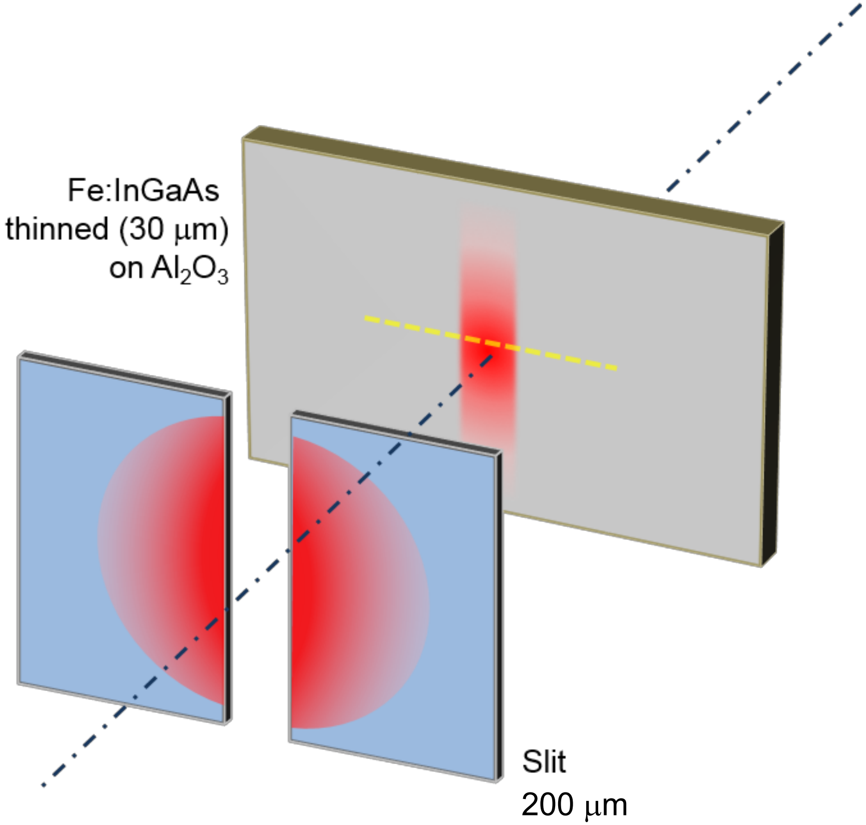
Generated THz field distribution in near-field

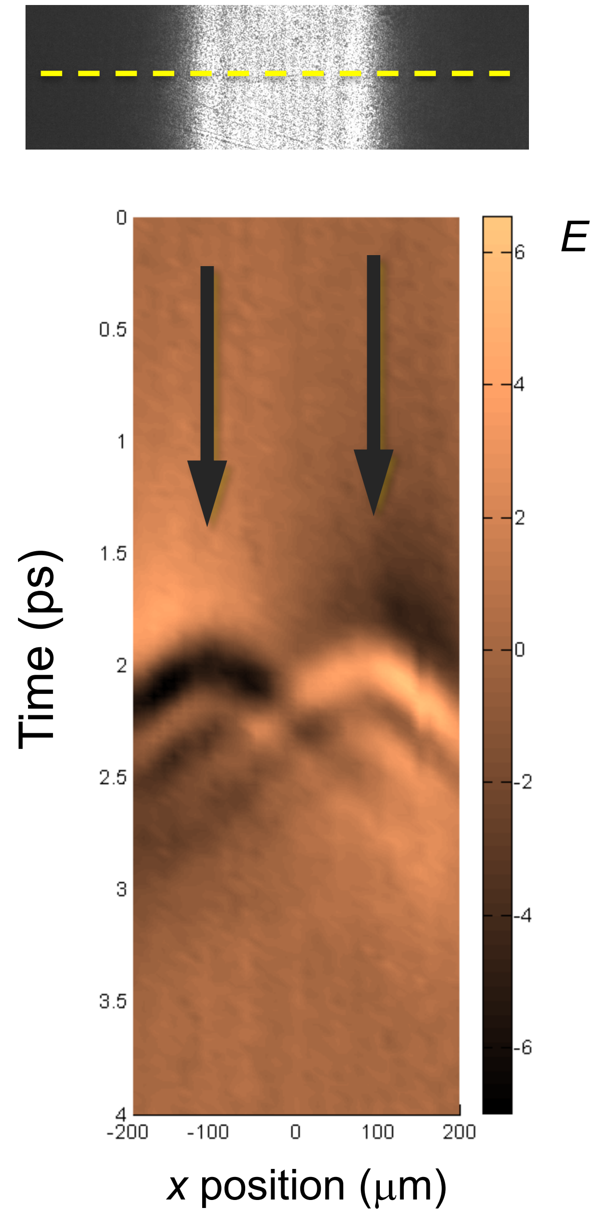




Mitrofanov et al.,
IEEE Trans. THz S&T (2016)

Generated THz field distribution in near-field



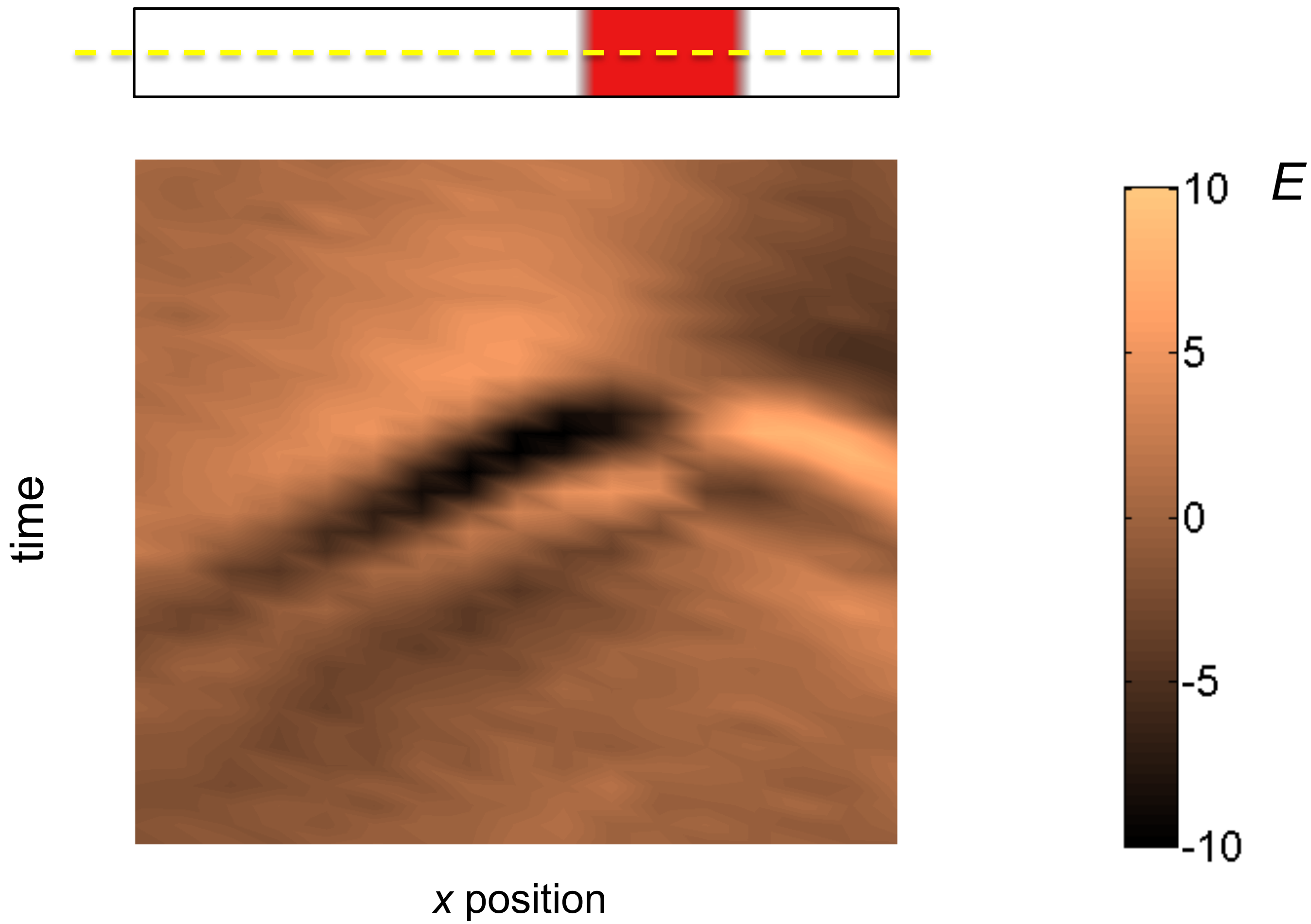


THz emission originates from two distinct points corresponding to the *slit edges.*

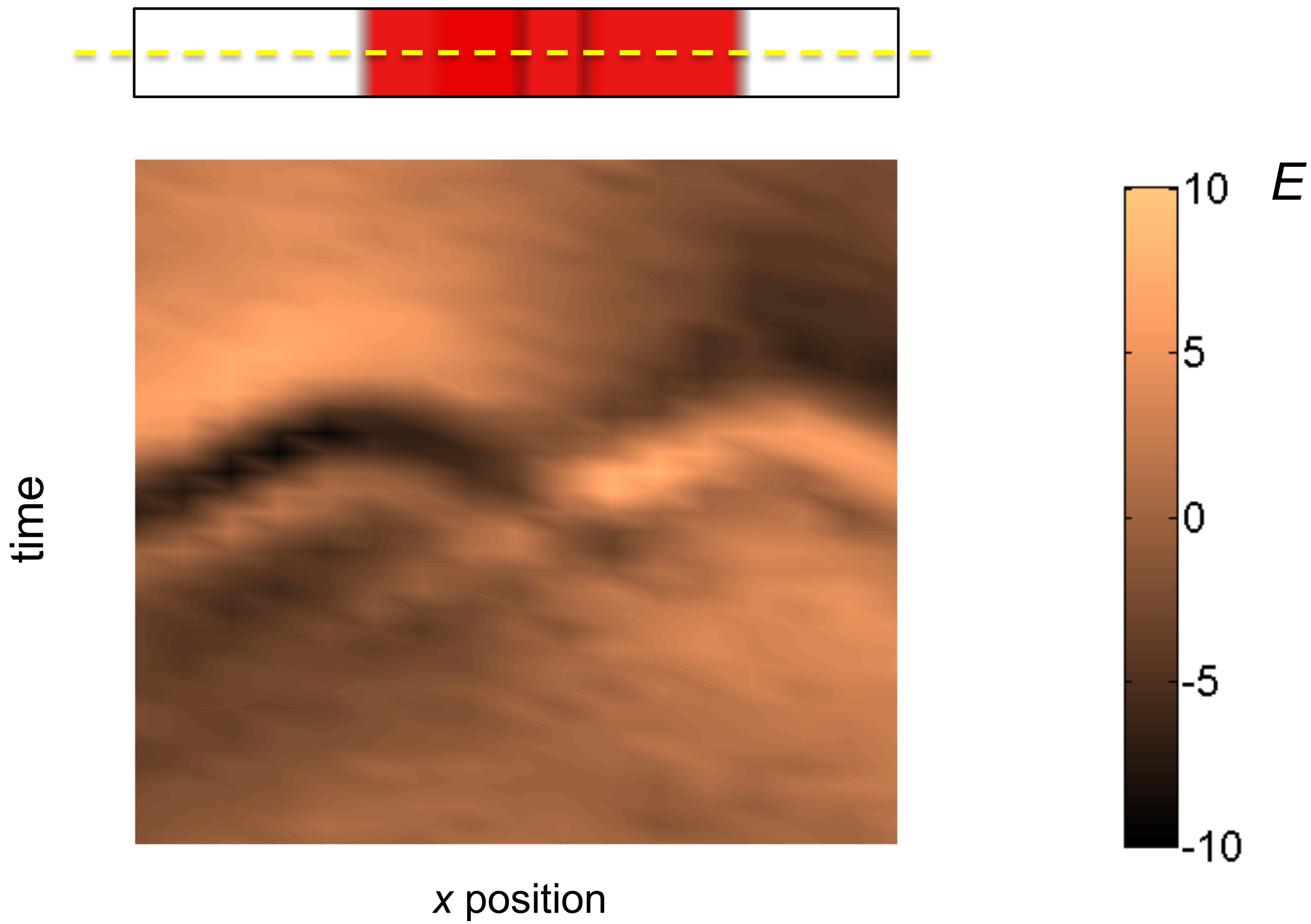
The two sources display opposite polarities leading to no emission in forward direction

Mueckstein et al.,
IEEE Trans. THz S&T (2015)

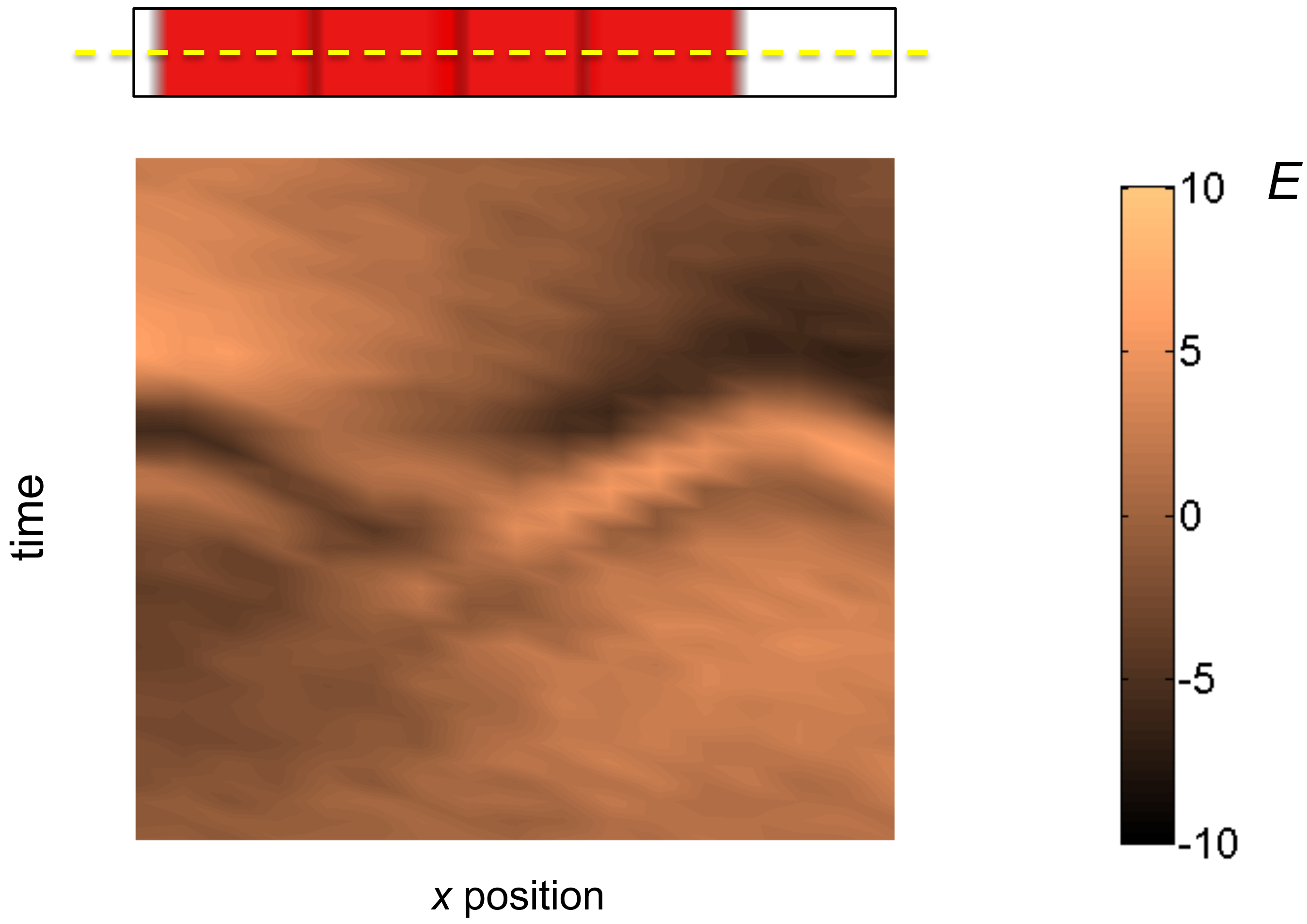
Effect of the excitation region width



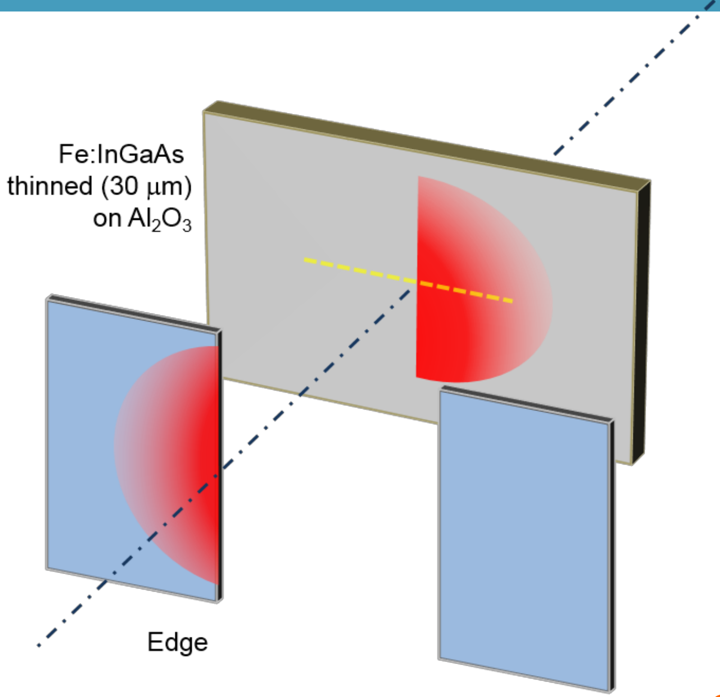
Effect of the excitation region width

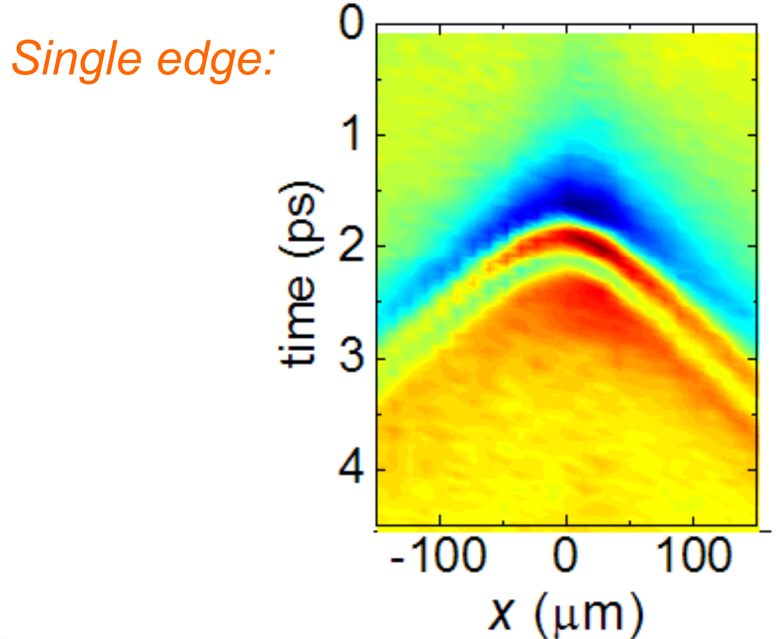


Effect of the excitation region width



Single edge





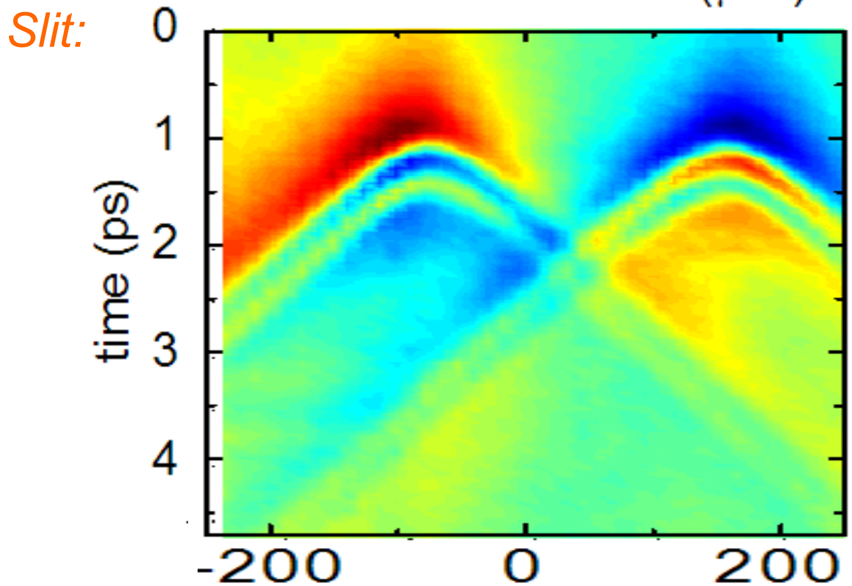


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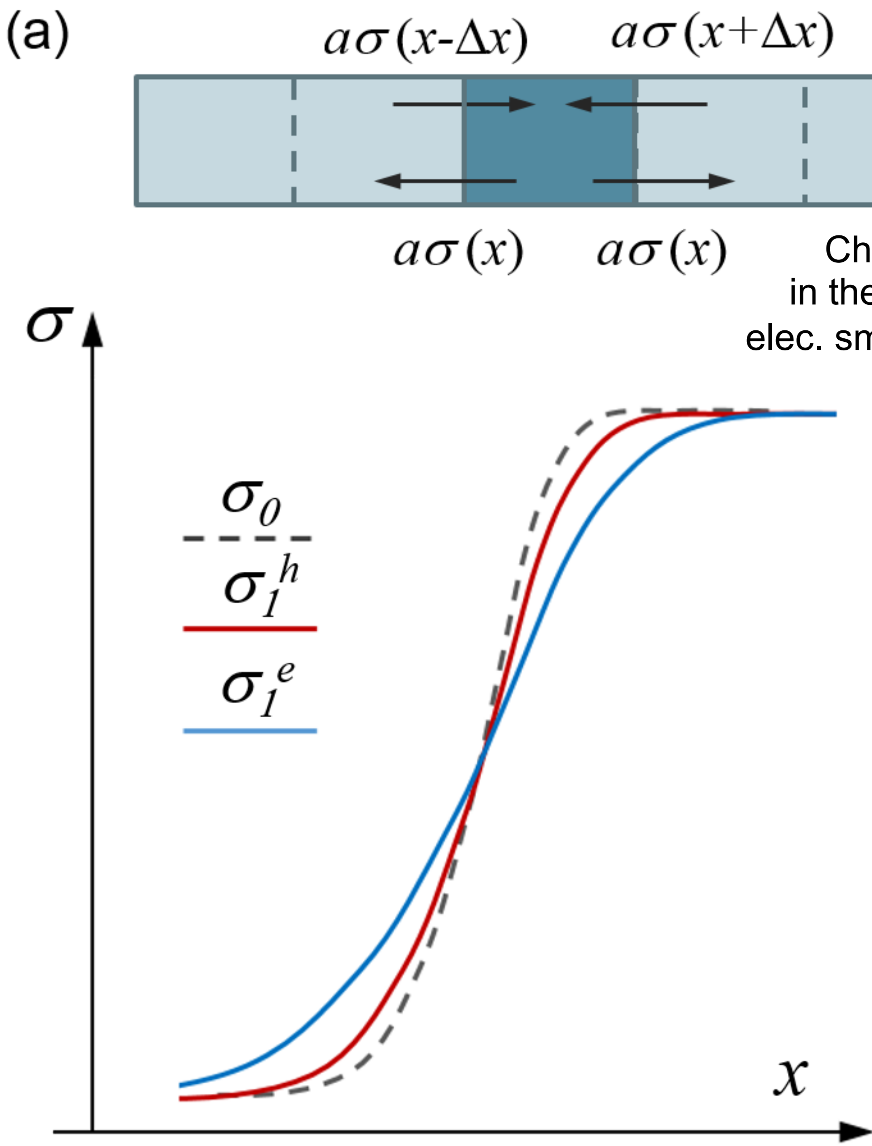
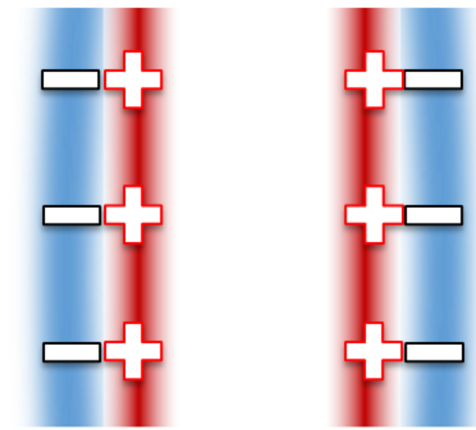
 Photo-excited charge carrier expansion

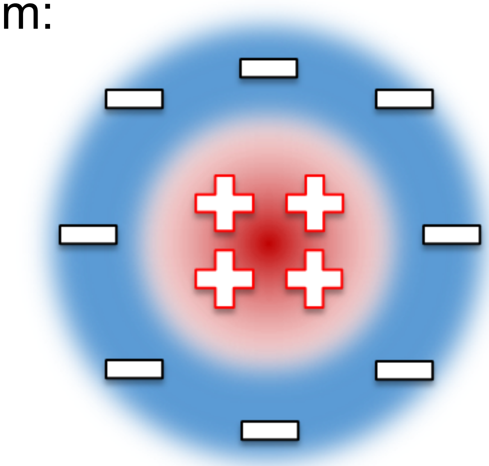


Charge current in the direction of elec. smaller density

Slit:



Beam:



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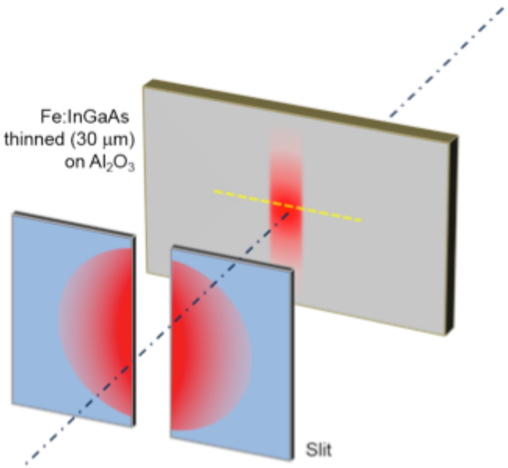
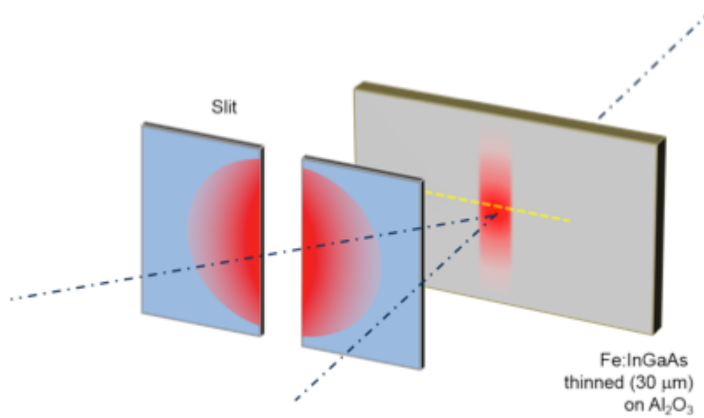
Normal incidence vs. 45 degree incident angle

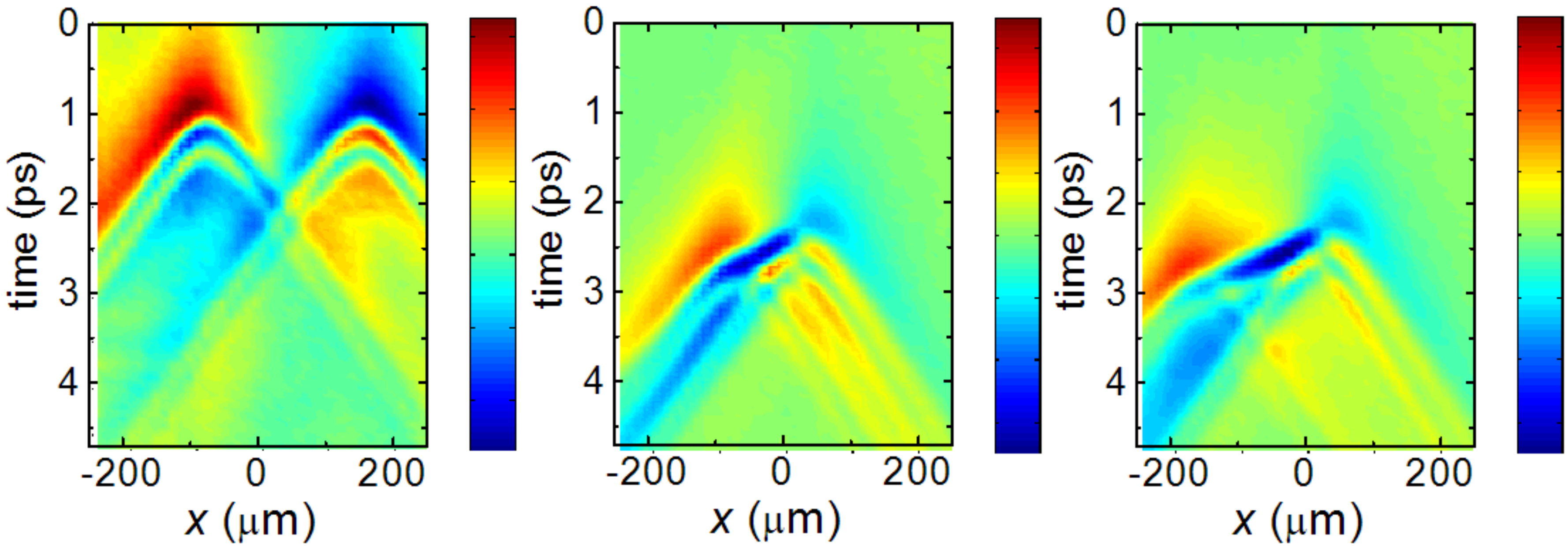




Normal incidence, 220 μm

45 deg., 150 μm

45 deg., 250 μm



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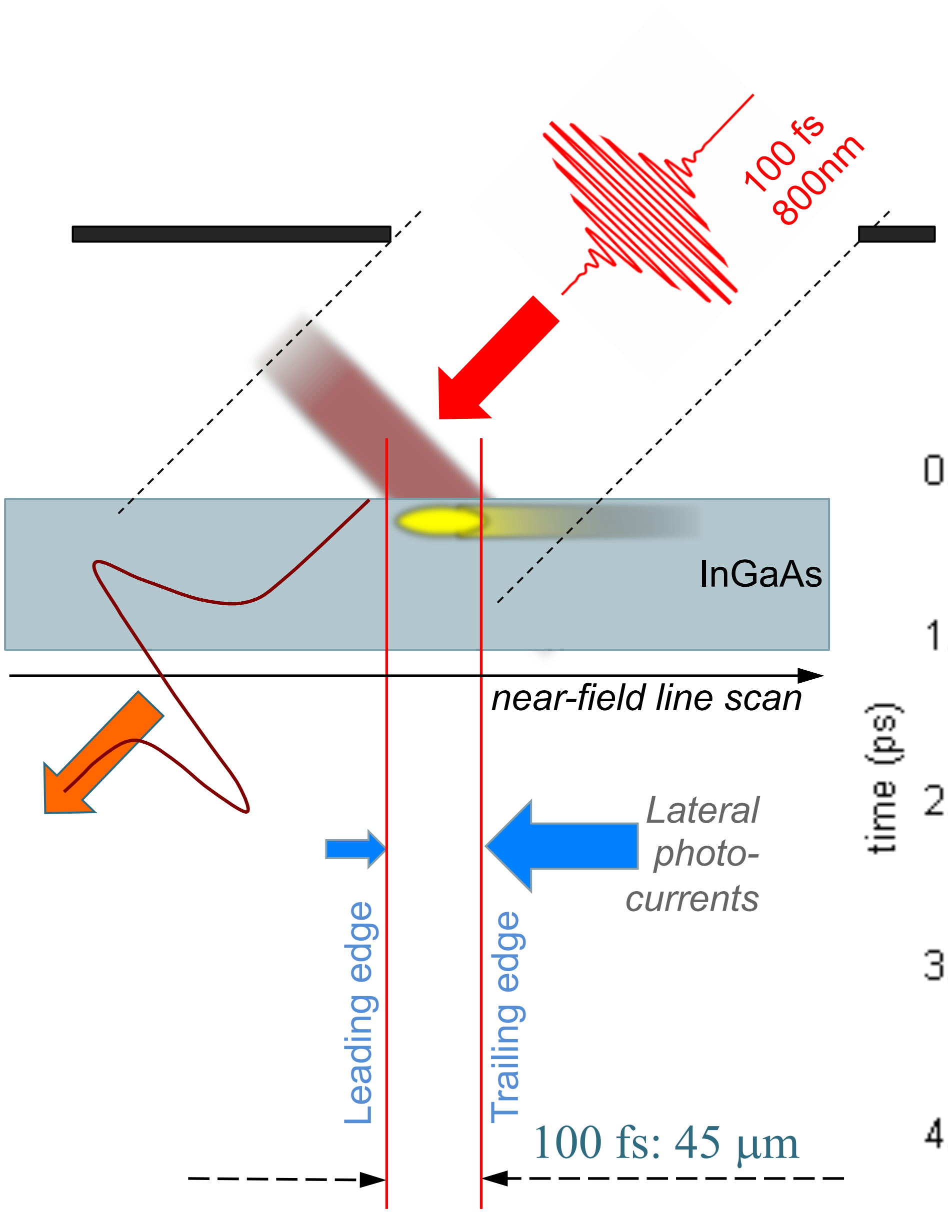
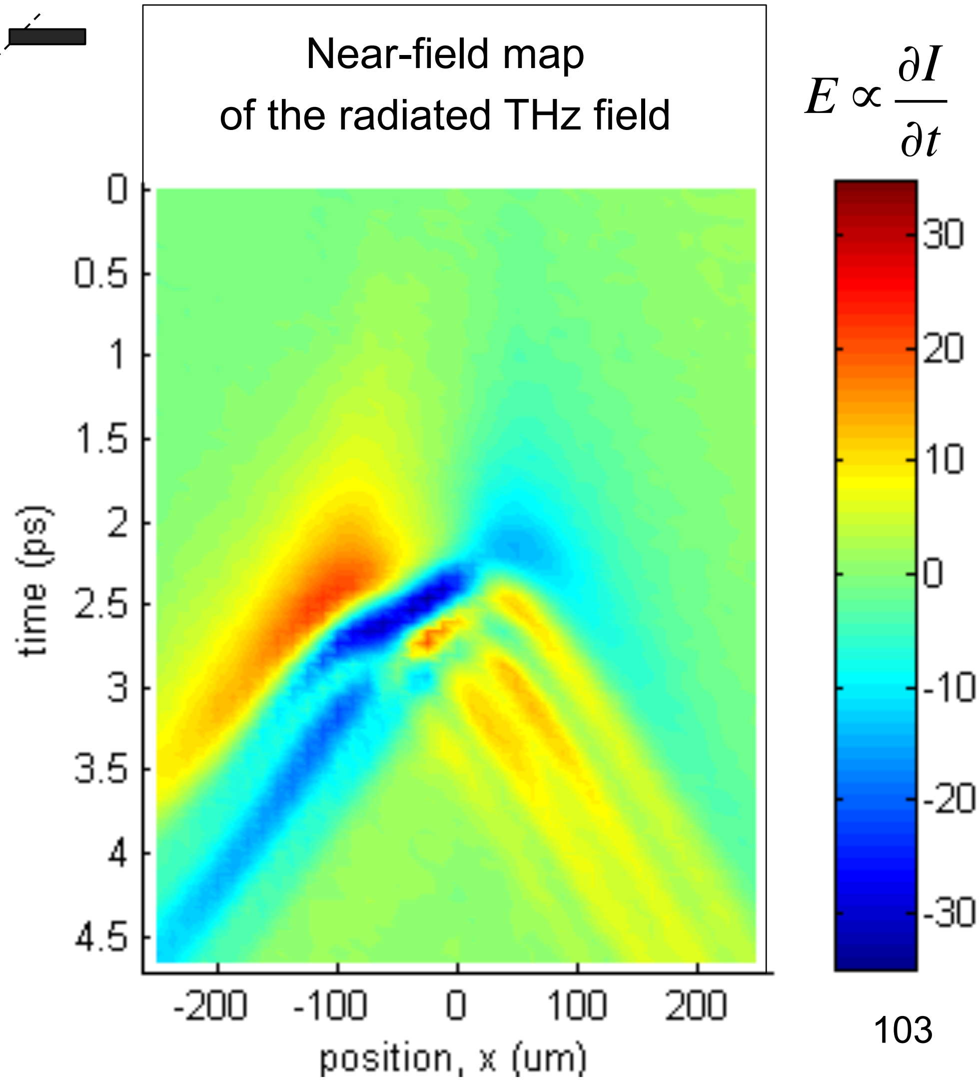
THz emission for the angle of incidence of 45 deg





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Emission of THz pulses